Nuclear Physics TABLES and An Introduction to Nuclear Physics

NUCLEAR PHYSICS TABLES

by J. MATTAUCH, Kaiser Wilhelm-Institut für Chemie, Berlin-Dahlem

and

AN INTRODUCTION TO NUCLEAR PHYSICS

by S. FLUEGGE, Kaiser Wilhelm-Institut für Chemie, Berlin-Dahlem

Translated from the German by
Eugene P. Gross and S. Bargmann

PUBLISHED AND DISTRIBUTED IN THE
PUBLIC INTEREST WITH THE CONSENT OF
THE ALIEN PROPERTY CUSTODIAN UNDER
LICENSE NO. A-1136

1946

INTERSCIENCE PUBLISHERS, Inc., NEW YORK

Copyright, 1942, by Springer-Verlag OHG, Berlin, Germany
Copyright vested in the Alien Property Custodian, 1943, 1946, pursuant to law
Copyright, 1946, by INTERSCIENCE PUBLISHERS, Inc.
215 Fourth Avenue, New York 3, N. Y.

Printed in the United States of America

Preface to the German Edition

For some years, the rapid increase of literature in experimental nuclear physics has compelled every physicist working in this field to maintain a reference file or similar implement in order to keep track of the large amount of material. Such a file was maintained also in the Kaiser Wilhelm-Institut für Chemie, and constitutes the nucleus of this book. The authors hoped to embrace in the composition and publication as complete a collection of material as possible, and, corresponding to the increasing importance of nuclear physics, to make this accessible to a wide circle. The tables cannot and, naturally, should not replace the study of the original papers; rather, they should be regarded as a guide, helping to locate quickly all the literature concerning any question. It has appeared especially important, therefore, to supply every entry in the tables with the necessary references. In this manner, over one thousand original papers have been included. The irregular flow of foreign periodicals since the start of the war has caused some difficulty, but all literature which was received in this institute until the end of August, 1941, and, in particular, all relevant papers appearing in *Physical Review* until the middle of 1941, have been included.

In order to make the tables easier to use, especially for the numerous students who are now entering more thoroughly into the field of nuclear physics, it has appeared desirable to accompany the tables with an introductory text. Good textbooks on the nucleus are not lacking, but these treatments are all five or more years old, and a glance at the contents clearly illustrates the significance of such a time lag in nuclear physics. The fundamental subjects of K-capture, isomerism, and meson theory of nuclear forces are included in this presentation for the first time. Moreover, all earlier presentations approach this subject more from the radioactive point of view. Topics like the optical determination of nuclear spin or the mass-spectrographic determination of isotope abundance and precision values of atomic masses, because of the methods involved, have been assigned to general atomic physics and, as a rule, only the results have been used. Applying to the text the principle of the tables—that all values are to be accompanied by references—led to a discussion of the experimental methods used to obtain these values. Here, probably for the first time, is a presentation of nuclear physics in which so-called bordering subjects are completely treated.

Extraneous circumstances have long delayed printing of this work. We are especially grateful to the publishers not only for the usual excellence of the format, but also for their appreciation of the need, during publication, for corrections due to the appearance of current literature, and for their mastery of the difficulties of printing.

THE AUTHORS

Berlin-Dahlem, October, 1941

CONTENTS

AN INTRODUCTION TO NUCLEAR PHYSICS

by S. FLUEGGE

PAGE

I. Stable Nuclei 1

A. Isotopes and Mass Numbers 1

1. Concept of Isotopy 1
2. Detection of Isotopy by the Parabola Method 2
3. Mass Spectrography 3

B. Mass Defects 8

4. Precision Measurements 8
5. Mass Defect and Packing Fraction 11

C. Nuclear Masses and Extranuclear Electrons 12

6. Nuclear Masses and the Atomic Spectrum 12
7. Nuclear Masses and the Rotation Spectrum 14
8. Nuclear Masses and the Rotation Vibration Spectrum 15

D. Relative Abundance and Atomic Weight 17

9. Chemical and Physical Mass Scales 17
10. Limits of Constancy of Relative Abundance 18

E. Nuclear Spin 19

11. Concept of Spin 19
12. Nuclear Spin from the Rotation Spectrum 21
13. Nuclear Spin from the Raman Spectrum 23
14. Nuclear Spin from Rotational Energy 25

F. Nuclear Magnetic Moment 28

15. Hyperfine Structure 28
16. Atomic Beam Method 32
17. Sign Determination and Resonance Method 35

G. Quadrupole Moment 38

18. Determination of Quadrupole Moment from H.F.S. 38

II. Nuclear Reactions 41

19. Methods of Observation 41
20. Sources of Radiation 49
21. Range–Energy Relation 54
22. Conservation of Energy and Momentum in Nuclear Reactions 57
23. The Neutron 60
24. Yield of Nuclear Reactions 64
25. Survey of Known Types of Reactions. Fission of the Heaviest Nuclei 71

PAGE

III. Unstable Nuclei 75
26. Natural Radioactivity 75
27. α-Disintegration 80
28. β-Disintegration 83
29. K-Capture 91
30. γ-Disintegration and the Problem of Isomerism 93

IV. Systematics of Stable Nuclei 97
31. Existence Rules 97
32. Binding Energy of Atomic Nuclei 99
33. Abundance Rules 102

NUCLEAR PHYSICS TABLES

by J. MATTAUCH

Explanation of Tables 105
Table I. Properties of Stable Nuclei 110
Table II. Maximum Possible Abundance of Probably Nonexistent Nuclei 120
Table III. Mass-Spectrographic Measurement of Doublets 122

Literature, Tables I–III 123
Table IV. Survey of Known Nuclear Reactions; Properties of Artificially Radioactive Nuclei 126
Table V. Supplement to Table IV 160
Table VI. Energy Release in Nuclear Reactions 160

Literature, Tables IV–VI 163

PLATES

Plate I. Packing Fraction and Mass Defect Curves
Plates II–VIII. Known Nuclei and Reactions on an N–Z Diagram

AN INTRODUCTION TO NUCLEAR PHYSICS

BY S. FLUEGGE

I. STABLE NUCLEI

A. Isotopes and Mass Numbers

1. Concept of Isotopy

Nearly all statements concerning the electronic envelop of the atom are independent of the mass of the nucleus and refer only to its charge, Z. Therefore, the chemical elements may be defined entirely by the nuclear charge number, Z, or equivalently by the number of extranuclear electrons in the neutral atom. No statement at all is made with regard to the mass of the atom; nevertheless, the chemical elements defined in such a manner possess characteristic combining weights. As a matter of fact, the classification in the periodic system was first achieved with the aid of atomic weights, and only much later was recognized really as a grouping according to nuclear charge number. This relationship becomes especially clear in the case of the two elements potassium and argon, where, notwithstanding its higher atomic weight, argon ($Z = 18$) precedes potassium ($Z = 19$) in the periodic system. We can, therefore, make the following statements:

An atom of a given fixed charge has a fixed mass (a rough statement which we shall refine).

A close correlation exists between atomic weight, A, and nuclear charge, Z. The ratio A/Z is approximately a constant for all elements. The value of this constant is about 2 but slowly increases to 2.6 with increasing Z.

The usual present-day scale of chemical combining weights is based on the convention that the mass of the neutral oxygen atom equals 16. In this scale the masses of many elements are approximately integers, e.g., hydrogen 1.008. There is also a series of marked deviations from the integer weight rule, e.g., chlorine (35.46) or copper (63.57). Crookes, in 1886, had already conjectured that atomic weights must, in general, be integral. The rather frequent exceptions are explained by the existence, for example, of several different types of chlorine atoms with integral masses of 34, 35, 36 in fixed and chemically unchangeable ratios, so that the combining weight 35.46 is only simulated by such a mixture. Elements with integral chemical combining weights would then be simple elements, which should consist of only a single type of atom. This conjecture of Crookes was later proved correct.

Atoms with the same nuclear charge number but with different mass numbers, A, are now called isotopes. Most of the elements possess several isotopes, present in practically constant ratios in a given element. Thus, the chemical element chlorine consists of two isotopes of mass numbers 35 and 37 in the ratio of about 3:1.

2. Detection of Isotopy by the Parabola Method

The separation of different mass components of a given chemical element was first achieved by J. J. Thomson in 1913, using his parabola method, schematically shown in Figure 1. A canal ray of neon ions passes through a small hole in the cathode, K, of a large discharge tube, R (voltage about 30 to 50 kV). This beam consists of ions which are formed in the discharge space by electron impacts, are drawn to K by the potential drop between the cathode and the anode, A, and reach the hole at a proper angle. Consequently the beam is defined by the geometry of the tube, which must be as narrow and long as possible, although the intensity, as in the pinhole camera, becomes extremely small. The hole in the cathode leads on the left to the deflecting space. Here the positive ions are subjected simultaneously to the action of a magnetic and an electric field. In the figure both fields act from top to bottom. The iron pole pieces, P, of the electromagnet, M, are insulated

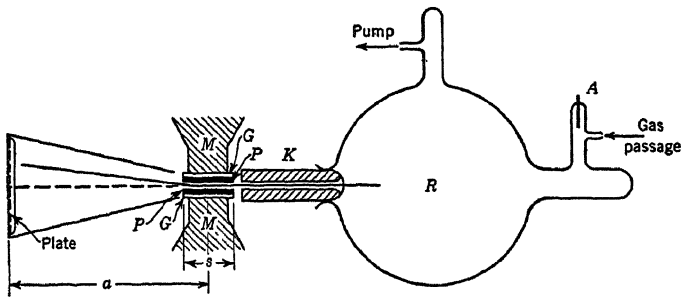


FIG. 1. Experimental setup in J. J. Thomson's parabola method.

by thin mica plates, G, so that a potential difference may be applied to them as condenser plates. If s is the length of the deflection space and e, M, v are the charge, mass, and velocity of the passing ions, the electric field, E, acting from above to below causes a deflection in the vertical direction:

$$y_1 = \frac{1}{2}\frac{e}{M}E\frac{s^2}{v^2} \tag{1}$$

Since the magnetic field of strength H is parallel to the electric field, it bends the path of the ion into a circular arc in a plane at right angles to the paper. As long as this deflection is small enough so that the circular arc can be approximated by a section of a parabola, it is:

$$x_1 = \frac{1}{2}\frac{e}{M}\frac{H}{c}\frac{s^2}{v} \tag{2}$$

Equation (1) is obtained in the following manner: The electric field acts like a gravitational field with acceleration $g = eE/M$. In the time $t = s/v$, which the ion requires to travel through the distance s, the distance that the ion falls will be $^1/_2\, gt^2$; this gives expression (1) directly. It is well known that the deflecting magnetic force is of magnitude $e/c \cdot Hv$ so that the acceleration in the field is $(e/Mc)Hv$. Using this, an easy calculation gives Equation (2).

If a photographic plate is placed at a distance a from the center of the deflection space, the beam will strike the plate at a point with coordinates:

$$x = \frac{e}{M}\frac{H}{c}\frac{a}{s}\frac{s^2}{v}, \qquad y = \frac{e}{M}E\frac{a}{s}\frac{s^2}{v^2} \tag{3}$$

Since ions are formed at all places in the discharge tube, one finds ions of all velocities between zero and a maximum velocity corresponding to the tube potential, V, according to:

$$\frac{M}{2} v_{max}^2 = eV \tag{4}$$

Hence, not a single point but an entire series of points corresponds to a single type of ion and blackens the plate. These points lie on the parabola:

$$y = \frac{Ec^2}{asH^2} \frac{M}{e} x^2 \tag{5}$$

Thus, the width of this parabola, besides depending upon the constants of the apparatus (a, s) and the applied fields (E, H), depends only upon the ratio of the ion mass, M, to the ion charge, e. Only integral multiples of the known elementary charge, e, occur, and actually a doubly ionized neon atom is very much more improbable than a singly ionized atom. Besides, the foregoing difficulties are not serious since the masses are approximately known and one can, therefore, distinguish between the curves which belong to different ion charges. These give no more trouble than the higher-order images of an optical diffraction grating.

In the classical Thomson experiment with neon, lines appeared at mass numbers 1, 2, 12, 28, 44, 100, and 200. These arose from impurities which could be assigned to ions H^+, H_2^+, C^+, CO^+, CO_2^+, Hg^{++}, and Hg^+. Besides these, two distinct lines appeared at mass numbers 20 and 22 which arose from singly charged neon, line 20 being about 10 times as strong as line 22. The obvious possibilities that line 22 was due to CO_2^{++} or to NaH_2^+ could be dismissed, since it was possible to remove completely the CO_2^+ line without any change in the intensity ratio of lines 20 and 22. It was also shown that, by adding helium, it was possible to produce a companion line HeH_2^+ to the He^+ line. This proved that neon consists certainly of two isotopes of mass numbers 20 and 22 occurring in the ratio 10:1.

The principal significance of the parabola method lies in Thomson's pioneer work. Its technical development later led to many sharper and better pictures. On account of its convenient operation it is even today often used for preliminary observations. For example, Schütze set up such an arrangement in order to check experiments on the enrichment of rare isotopes. A few years ago Zeeman and de Gier determined the relative abundance of the different isotopes of nickel and some other elements by this method.

3. Mass Spectrography

The small intensities involved in the parabola method constitute an important defect. A basic improvement may be obtained by working with crossed rather than with parallel fields; the magnetic and electric field deflections are then no longer at right angles to each other but are in the same direction. Each ray of a given mass, charge, direction, and velocity then corresponds to a given point on the photographic plate and these points are arranged in a "spectrum." If direction and velocity be maintained within narrow limits, it is evident that a series of spots, i.e., a line spectrum, will be obtained, in which each line corresponds to a given value of M/e. An arrangement by which such a mass spectrum may be photographed is called a mass spectrograph.

The intensities obtained by the mass-spectrograph method are not greater than those in the parabola method, since the selection of a narrow velocity interval decreases the inten-

sity as much as it is increased by the contraction of the entire parabola to a point. The decisive advance inherent in this apparatus rests more upon the fact that, by proper choice of deflecting fields, the beam may be focused. Focusing directs all particles of equal M/e, but of different velocities, to the same point on the plate and in this manner permits the use of a broad velocity band (Aston's arrangement). An alternative method is to employ only a narrow velocity interval, but to focus the different directions, so that rather open, more intense beams may be used (Dempster's setup). This improvement evidently corresponds exactly to the transition in photography from the pinhole camera to lens optics. Recently, mass spectrographs with double focusing in regard both to directions and velocities have been constructed (Mattauch and Herzog, Dempster, Bainbridge and Jordan). In the following we shall briefly discuss the most important of these types.

1. Aston's Velocity Focusing. Different velocities of ions correspond to different wavelengths of light in optics. Aston's arrangement may be described optically as an achromatic set of two prisms without lenses. The principle of the arrangement is sketched in Figure 2. The ion beam comes from the left and is first deflected downward in the

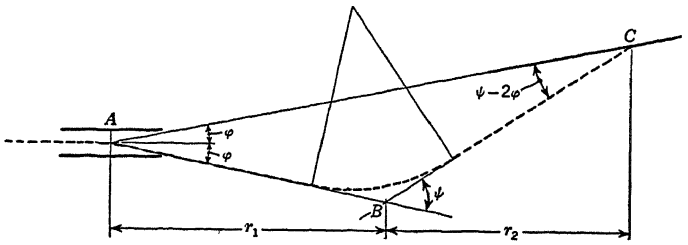


FIG. 2. Velocity focusing in Aston's mass spectrograph.

electric field by an angle, φ. As long as this angle is small we have, according to Equation (1):

$$\varphi = A/v^2 \tag{6}$$

where A is a constant dependent solely on the dimensions of the condenser, on M/e and on the applied voltage. Thus, it has the same value for all velocities. The beam then enters the magnetic field which deflects it back upward through the small angle, ψ. Here we have:

$$\psi = B/v \tag{7}$$

where B is again a constant independent of the velocity. With the indicated distances r_1 and r_2, the ray in traversing the entire length $r_1 + r_2$ is raised altogether by an amount:

$$-(r_1 + r_2)\varphi + r_2\psi$$

while the direction has changed by $\psi - \varphi$. This holds for a ray of velocity v. For a ray of somewhat different velocity, $v + dv$, the lifting amounts to:

$$-(r_1 + r_2)(\varphi + d\varphi) + r_2(\psi + d\psi)$$

and the direction is changed by $\psi + d\psi - \varphi - d\varphi$. The focusing condition now demands that both these changes coincide, so that:

$$-(r_1 + r_2)d\varphi + r_2 d\psi = 0 \tag{8}$$

even though the directions of both rays are different. Both rays will then intersect at C,

to which point the photographic plate is brought. By differentiation, one finds from Equations (6) and (7):

$$d\varphi = -\frac{2\,dv}{v}\,\varphi \text{ and } d\psi = -\frac{dv}{v}\,\psi$$

so that the focusing condition (8) becomes:

$$2(r_1 + r_2)\varphi = r_2\psi \tag{9}$$

We can now find the position to which the photographic plate must be brought. If we construct the triangle ABC in the diagram by drawing at A a line making an angle φ on the other side of the original ray, we obtain by applying the sine law:

$$\frac{\sin(\psi - 2\varphi)}{r_1/\cos\varphi} = \frac{\sin 2\varphi}{r_2/\cos(\psi - \varphi)}$$

Upon replacing the sine by its argument and the cosine by 1, there results:

$$r_2(\psi - 2\varphi) = 2\,r_1\varphi$$

which is identical with Equation (9). The focal line to which the photographic plate is to be brought is thus the straight line AC, so long as the deflecting angles remain small.

2. Dempster's Direction Focusing. If particles of equal velocity enter a magnetic field under not too large an angle of opening, they will converge to a point after they are deflected through 180°. Classen used this fact a long time ago to make e/m determinations with cathode rays. Dempster's 1918 setup also utilizes this basic principle, as shown in Figure 3. At S ions enter the magnetic field, in which they describe circles of different radii according to the value of M/e. If the strength of the magnetic field is changed, the rays with different M/e ratios fall one by one on the collecting slit, F, at the end of the field and are detected by the current flowing from A to the galvanometer, G. Since velocity focusing is relinquished in this method, care must be taken that only ions of rather homogeneous velocity enter the field at S. The mass spectrographs constructed until now according to this principle differ in the manner in which this requirement is achieved. The most important types are enumerated in the following:

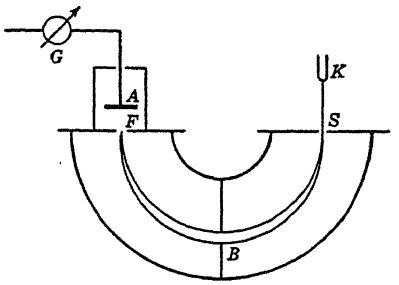


FIG. 3. Principle of direction focusing in Dempster's mass spectrograph.

(a) In Dempster's first arrangement (1918), the ions were produced by heating of salts on platinum strips or by bombardment of these salts by electrons. Later (1922) the metal itself was vaporized and the vapor ionized by electronic collision. The ions are then accelerated by an electric potential, V, which exists between a slit near the cathode, K, and the entrance slit, S. Since V is large compared to the energy (expressed in volts) with which the particles enter the accelerating space, they will all be brought to practically the same energy:

$$\frac{1}{2}Mv^2 = eV$$

(b) Bleakney (1929) and Bainbridge (1930) obtained a homogeneous velocity by means of a Wien filter. The ion beam, its direction determined by means of apertures, is

sent through a condenser in which it experiences a downward acceleration of magnitude:

$$b_1 = \frac{e}{M} E$$

A magnetic field is simultaneously applied at right angles, imparting to the beam an upward acceleration:

$$b_2 = \frac{e}{M} H \frac{v}{c}$$

Evidently only those ions which remain undeflected, i.e., for which $b_1 = b_2$, can pass the system of apertures. This holds for all ions of velocity:

$$v = cE/H$$

independent of their different masses and charges. Only these ions survive in the magnetic field.

(c) Smyth (1926) developed a procedure which Smyth and Mattauch used in 1932 for the construction of a mass spectrograph. The beam passes successively through two condensers of length s, to which an alternating electric field is applied. Again in this apparatus, a similar aperture system provides passage only for those particles which remain undeflected. The time required to pass the first condenser is $t = s/v$. If the frequency is chosen so that $\omega \cdot s/v = 2\pi n$ (n is an integer), every passing particle will experience as many thrusts upward as downward. No change of direction is observed, but only a parallel displacement of path which is dependent on the phase at which the ionized particle enters the condenser. Evidently the same displacement of path occurs in the second condenser. The entrance phase at the second condenser must be chosen in such a way that the parallel displacement which the ion experiences in the first condenser is annulled in the second; this occurs when the entrance phase at the second condenser differs by exactly π from that at the first. The required phase difference is achieved by choosing the distance a between the initial edges of the condensers so that $\omega \cdot a/v = \pi(2m + 1)$ is an odd multiple of π. The simultaneous satisfaction of both these conditions gives:

$$a/s = (2\,m + 1)/2\,n = \text{odd number/even number}$$

All velocities which satisfy the condition:

$$v = \frac{\omega s}{2\pi n}$$

are let through. The disadvantage of this arrangement lies in the number of velocity groups passing through. For example, if one makes:

$$a/s = 3/2 = 9/6 = 15/10 = \ldots$$

the velocities:

$$v = \frac{\omega s}{2\pi} \quad \frac{\omega s}{2\pi} \cdot \frac{1}{3} \quad \frac{\omega s}{2\pi} \cdot \frac{1}{5} \ldots$$

will pass through the filter.

(d) Nier (1936) set up an arrangement (Fig. 4) which resembles most closely the original Dempster system and in which a homogeneous velocity beam is obtained by means of a method due to Bleakney. Electrons leaving a tungsten filament, G, are drawn to A by a small voltage between G and A (about 4 volts) and are then accelerated by a suitable voltage between A and B. These produce ions in the gas space between M and P_1. Furthermore, between M and P_1 a weak electric field exists which draws the ions to P_1. The ions which have passed the slit in P_1 (in the figure the slit appears in longitudinal cross section and, therefore, is very wide) are then accelerated downward to a uniform velocity by a high potential difference between P_1 and P_2. At P_2 they enter the 180° deflecting magnetic field. As in Dempster's method, the ion current is measured at the end of this deflecting field.

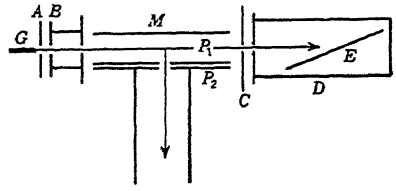


FIG. 4. Production of ions of uniform velocity by Bleakney's method in Nier's mass spectrometer.

3. Double Focusing. The modern development of electron optics has shown that, in addition to prism action, i.e., the unequally strong deflection of ions differing in velocity, electric and magnetic fields manifest a lens effect, i.e., the focusing of beams of different directions. We have become acquainted with an example of such direction focusing in the case of the homogeneous magnetic field deflecting through 180°. Another important special case is the electric radial field which deflects by an angle $180°/\sqrt{2} = 127.2°$. Fields which deflect through half the angle, such as a homogeneous magnetic field of 90° and an electric radial field of 63.6°, change a beam which is diverging from the point of entrance into a parallel beam, and thus possess the property of an optical collimator. The general theory of the lens and prism action of electric and magnetic fields was thoroughly studied by Herzog in 1934. On the basis of this work Mattauch and Herzog showed that double focusing can be achieved in the mass spectrograph by proper combination of fields. In the following discussion the most important types are set down briefly.

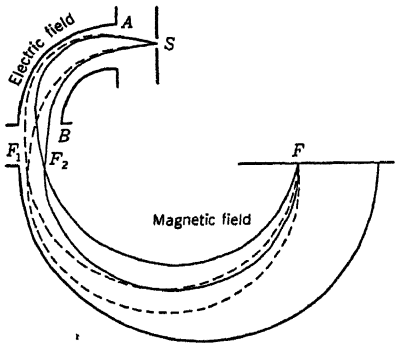


FIG. 5. Dempster's new double focusing setup. Beams with different directions are focused in the electric field, those of different velocities in the magnetic field.

(a) Dempster's new mass spectrograph (Fig. 5), completed in 1935, consists of a 90° radial field and a 180° magnetic field. The broken lines in the figure correspond to paths of particles with velocity v_1, the solid to velocity v_2. Beams which enter under different angles are focused at F_1 and F_2, those of velocity v_1 at F_1 and those of velocity v_2 at F_2. For each mass a velocity spectrum is traced out at this point. The magnetic field which follows then recollects at the point F all the divergent beams which leave F_1. An additional condition must be satisfied in order that the beams leaving F_2, possessing a greater velocity and hence a greater radius of curvature, reach the same point, F. Thus velocity focusing is also achieved. Dempster's spectrograph is so arranged that this condition is fulfilled for a given mass. The desired double focusing is then obtained for only a single spot on the photographic plate.

(b) In 1936 Bainbridge and Jordan published a similar arrangement, in which the preliminary focusing takes place in a 127° deflecting radial electric field while the attached

magnetic field deflects through only 60°. This arrangement has great advantages because of the expensiveness of magnetic field apparatus. Here, also, double focusing is obtained for only a single spot on the plate.

(c) In both the apparatus described, the simplest special case is chosen, in the one case for the magnetic, in the other for the electric field. The other field is then chosen in each instance so that double focusing sets in for a given mass. This last limitation may also be dismissed, and we may propose the following question: If we can choose freely the deflecting angles of both fields and the distance of the foremost slit from the electric field, i.e., the point from which the beam diverges so that focusing will obtain in the arrangement, is it then possible to achieve double focusing for more than one mass? The investigation by Mattauch and Herzog (1934) showed that this is, in fact, possible and that the problem has more than one solution. They built a mass spectrograph for the solution with deflecting angles of 31°50′ for the electric radial field and 90° for the magnetic field, which actually exhibited double focusing for every spot and, thus, for the entire mass scale. The arrangement, shown schematically in Figure 6, possesses the additional advantage that it has a simple mass scale since the distances are proportional to the square roots of the masses.

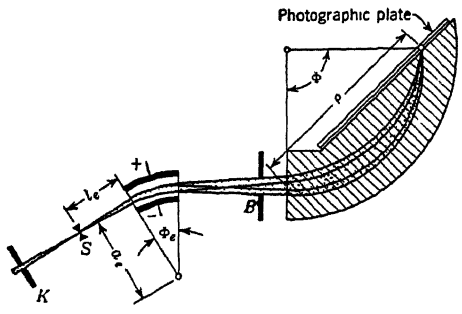


FIG. 6. Double focusing arrangement by Mattauch and Herzog. The beam leaving slit S is decomposed in the electric field into a number of parallel beams of different velocities, which are all reunited in the magnetic field into the same point on the plate.

B. Mass Defects

4. Precision Measurements

The mass spectrographic examination of almost all chemical elements, carried out in the twenties, chiefly by Aston, gave a general confirmation of Crooke's conjecture: Elements of integer atomic weight often proved actually to be pure elements, i.e., they consisted of only one type of isotope. In other cases it was shown that the integral property of the atomic weight was accidentally simulated by a special mixing ratio, e.g., in hydrogen, in which the isotope of mass 2 is very much rarer than the ordinary isotope of mass 1, or in bromine, where both isotopes of mass 79 and 81 are equally abundant, so that the atomic weight is integral (= 80). In all cases of nonintegral atomic weight, a mixture of several, and often numerous, isotopes ("components") of integral masses is present.

However, even the first experiments showed that this integral rule is not completely exact. As is known, the chemical atomic weights of hydrogen and oxygen are not exactly in the ratio 1:16 but 1.008:16. Since oxygen was held at first to be a pure element, the obvious suggestion was to look into the existence of a heavy hydrogen isotope of mass 2, which would then make up 0.8% of ordinary hydrogen, and to which this deviation from the integral state could be attributed. In 1919 Stern and Volmer failed to find such an isotope. They also ruled out the possibility that the deviation was simulated by the existence of a lighter oxygen isotope (of about mass 15). This showed for the first time that the integer weight rule of isotope masses holds only approximately.

Thus the task of performing precision measurements arose in order that one could make

determinations of deviations from the integer rule, which are of the order of magnitude of several per thousand. Aston had already taken the first step towards developing mass spectrography as a precision method. Since in the mass spectrum the apparent mass of an n-fold ionized particle of mass M amounts only to M/n, and since molecular ions as well as atomic ions are present, the same mass number may be occupied by different ions, e.g., mass number 16 by O^+ ions as well as by singly ionized methane molecules $^{12}C\,^{1}H_4^+$. If the masses of the atoms concerned were exactly integral, the spectral lines belonging to both would be exactly superposed. Actually, the CH_4^+ line does not lie at mass 16, but at mass 16.036. If the mass of hydrogen ^1H is taken from chemistry as 1.008, the mass of ^{12}C relative to $^{16}O = 16$ can be determined as $^{12}C = 16.036 - 4 \cdot 1.008 = 12.004$.

The important fact regarding the so-called "doublet method" is that the numbers 16.036 and 16.000 themselves do not need to be measured with this accuracy of 1/16,000, but it is sufficient that the distance 0.036 between the two lines be measured exactly to within 3%, in order that both masses be obtained with a precision of 0.001. In this connection, care must be exercised that the dispersion and resolving power of the mass spectrograph are large enough to separate both lines clearly.

The tasks of mass spectrography, then, fall into two distinct groups: Either the determination of mass numbers and abundances with relatively low dispersion instruments, or precision methods on masses by resolution of narrow doublets or multiplets of mass lines. Different construction types correspond to the two different tasks. Of the instruments found today, especially those of the Dempster type, have been used for the first task (page 5). Aston's more recent apparatus (page 4) and the double-focusing instruments of Bainbridge and Jordan, Dempster, and Mattauch and Herzog (pp. 7, 8), with their higher dispersion and resolution, are especially used for the purpose of precision measurement.

All modern precision measurements are related to the standard, $^{16}O = 16$. For this purpose a system of three easily accessible substandards was measured with great accuracy. The three substandards are the isotopes ^1H (light hydrogen), ^2H (also written ^2D) (heavy hydrogen), and ^{12}C (carbon). The determination of these is achieved with the help of three fundamental doublets:

$$^{12}CH_4^+ - {}^{16}O^+ = \alpha \text{ at mass number } 16$$

$$^{2}D_3^+ - {}^{12}C^{++} = \beta \text{ at mass number } 6$$

$$^{1}H_2^+ - {}^{2}D^+ = \gamma \text{ at mass number } 2$$

The masses themselves may be calculated from these differences, and one finds:

$$^{2}D = 2 + \frac{1}{8}\alpha + \frac{1}{4}\beta - \frac{1}{4}\gamma$$

$$^{1}H = 1 + \frac{1}{16}\alpha + \frac{1}{8}\beta + \frac{3}{8}\gamma$$

$$^{12}C = 12 + \frac{3}{4}\alpha - \frac{1}{2}\beta - \frac{3}{2}\gamma$$

The most recent measurements of substandards, carried out in the last few years at three different places, are recorded in the accompanying table.

Type of atom	Mass relative to ^{16}O = 16 according to measurements of		
	Mattauch-Bönisch	Bainbridge-Jordan	Aston
$CH_4 - O = \alpha$	0.0036406 ±0.000040	0.03649 ±0.00008	0.03601 ±0.00016
$D_3 - C^{++} = \beta$	0.042239 ±0.000021	0.04219 ±0.00005	0.04236 ±0.00018
$H_2 - D = \gamma$	0.001539 ±0.000002	0.00153 ±0.00004	0.00152 ±0.00004
^1H	1.008132 ±0.000004	1.00813 ±0.00002	1.00812 ±0.00004
^2D	2.014726 ±0.000008	2.01473 ±0.00002	2.01471 ±0.00007
^{12}C	12.003876 ±0.000032	12.00398 ±0.00009	12.00355 ±0.00015

For the first of the three doublets there exists, in addition, a precision measurement of Asada, Okuda, Ogata, and Yoshimoto, whose result (α = 0.03642 ± 0.00009) agrees well with the data of Mattauch and Bainbridge. In the table a weighted average of the results of all the cited authors has been taken.

The precision measurements of doublets obtained until now, as well as the somewhat less exact doublet measurement of Dempster and Graves, are collected in a special table.

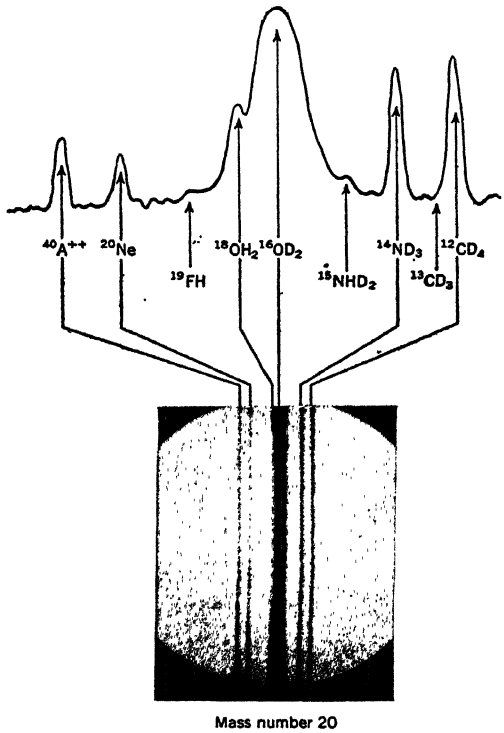


FIG. 7. Example of the resolving power of a modern mass spectrograph: structure of the line at mass number 20.

In order to give a clear idea of the attainable exactness, Figure 7 shows the multiplet structure of the line at mass number 20 according to a picture by Mattauch. The picture of the photographic plate as it is seen in the microscope is reproduced underneath, while above is the corresponding microphotometer curve assigning the peaks to the individual isotopes.

The total distance from the farthest line at the left ($^{40}A^{++}$) to the farthest at the right ($^{12}C\ ^{2}H_4^{+}$) is not more than 0.075 mass units, i.e., nearly 0.4% of the total mass 20!

5. Mass Defect and Packing Fraction

The masses given here and in the tables are always those of the neutral atoms. We obtain the masses of the nuclei by deducting the masses of Z electrons, each of which possesses a mass of 0.000547. For example, the mass of the proton is 1.00813 − 0.00055 = 1.00758.

According to present ideas an atomic nucleus of mass number $A = Z + N$ consists of Z protons and N neutrons. Consequently the neutral atom should have the mass of Z neutral hydrogen atoms plus N neutrons. On page 10 we have already specified the mass of the hydrogen atom (1.00813). Later (page 62), we shall see that the mass of the neutron is 1.00895. As a result, the mass of a neutral atom with nuclear charge Z and mass $A = Z + N$ should be:

$$Z \cdot 1.00813 + (A - Z) \cdot 1.00895 = A(1 + 0.00895 - \frac{Z}{A} 0.00082)$$

or approximately 0.8% larger than the mass number. Actually the deviation from integer weight is, in general, much smaller and, excepting the lightest and heaviest elements, the deviation is always negative in sign. All atomic nuclei exhibit a mass defect of the order of magnitude of 0.8% with respect to the sum of the masses of the constituents. These mass defects are given in the tables in thousandths of a mass unit (10^{-3} MU) and, in addition, they are calculated on another scale (MeV) which we shall now discuss.

According to the theoretical ideas of present-day physics, it is clear that such a mass defect must exist. The nuclear constituents are bound together. Since work must be done to separate them, the total energy content of the system "nucleus" is smaller than that of the separated constituents. According to a fundamental postulate of the theory of special relativity, the mass of a system is only a measure of its energy content, where the energy and mass scales are connected by the relation:

$$E = Mc^2 \tag{10}$$

The mass defect is thus the binding energy of the atomic nucleus, which we can measure either directly on the mass scale (10^{-3} MU) or, more conveniently for physical applications, on the energy scale (MeV). We have defined the mass unit (MU) as $^1/_{16}$ of the mass of the neutral ^{26}O atom; this is actually $1.660 \cdot 10^{-24}$ g. In this scale the mass of a neutral H atom is 1.00813 MU. The relation which exists between the 10^{-3} MU and the energy of 1 MeV = 10^6 eV is:

$$10^{-3}\ \text{MU} = 0.931\ \text{MeV} = 1.493 \cdot 10^{-6}\ \text{erg}$$
$$1.074 \cdot 10^{-3}\ \text{MU} = 1\ \text{MeV} = 1.603 \cdot 10^{-6}\ \text{erg}$$

According to the foregoing, each constituent of the atomic nucleus (proton or neutron) contributes an average binding energy of 8 MeV independently of whether the nucleus is light or heavy. There are, naturally, exceptions to this rule. Thus, the binding energy of the heavy hydrogen atom (deuteron) is only about 2 MeV, and likewise the loosest neutron in ^9Be is bound as weakly. For the heaviest nuclei ($Z > 81$), the binding energy of the weakest constituents decreases to about 6 MeV. Naturally, it is by no means self-evident that just this order of magnitude of the binding energy should exist. Rather, the magnitude

of the binding energy is given by the magnitude of the binding forces between constituents by which the nucleus is held together. The fact that the mass defects fall into an order of magnitude which is still accessible to measurement is a great stroke of luck. This allows us, first of all, to test and confirm experimentally the basic postulate of relativity, $E = Mc^2$, and also permits us to obtain important conclusions concerning the structure of nuclei and the forces acting between its constituents, protons and neutrons.

For experimental practice it is often convenient to use, instead of the mass defect, D, another quantity, the so-called packing fraction, f. The packing fraction is obtained by dividing the deviation of the true atomic mass, M, from the integral mass number, A, by this mass number:

$$f = \frac{M - A}{A} \tag{11}$$

The packing fraction is most frequently given in terms of 10^{-4} MU. For the lightest and heaviest nuclei it is positive, while for the rest it is negative. The advantage of the packing fraction is that a knowledge of the exact masses of neutron and proton is not necessary to specify it; its drawback is that it does not permit as direct a physical interpretation as the mass defect. Between the two quantities, D and f, the following relation exists:

$$D = A(8.95 - \frac{Z}{A}\cdot 0.82 - f) \tag{12}$$

$$f = +8.95 - \frac{Z}{A}\cdot 0.82 - D/A$$

in which D and f are measured in 10^{-3} MU.

EXAMPLE: For the isotope ^{48}Ti, the packing fraction is $f = -7.13\cdot 10^{-4}$ MU (average of Dempster's and Aston's measurements), i.e., $f = -0.713\cdot 10^{-3}$ MU. Since $Z = 22$ and $A = 48$, the mass defect is:

$$D = 48(8.95 - \frac{22}{48}\cdot 0.82 + 0.71) = 48\cdot 9.29 = 446\cdot 10^{-3}\text{ MU} = 415\text{ MeV}$$

In this case the average binding energy of a constituent is $9.29\cdot 10^{-3}$ MU = 8.64 MeV.

C. Nuclear Masses and Extranuclear Electrons

6. Nuclear Masses and the Atomic Spectrum

As previously mentioned, the phenomena in the electron envelop of the atom are, to a first approximation, independent of the nuclear masses and determined only by the nuclear charge number, Z. All of chemistry and a great portion of atomic physics rest on this fact. However, a more exact examination shows an influence of the nuclear masses on electronic motion which can be studied in characteristic displacements of energy levels (hence, of spectral terms and of spectral line frequencies). Essentially three different influences due to the nucleus must be distinguished:

1. Motion of the Nucleus. Even in the simplest element, hydrogen, with only a single electron about the nucleus, an effect of this type enters: The electron does not circle

the motionless nucleus, but actually the mass center of the system, nucleus plus electron, is at rest, while the nucleus as well as the electron circles the common mass center. In the description of electron terms according to the Balmer term formula:

$$\nu_n = -\frac{2\pi^2 me^4 Z^2}{h^3 n^2} = -\frac{RZ^2}{n^2} \tag{13}$$

the reduced mass, m^*, instead of the electron mass, m, must be introduced:

$$\frac{1}{m^*} = \frac{1}{m} + \frac{1}{M}; \qquad m^* \approx m\left(1 - \frac{m}{M}\right) \tag{14}$$

Correspondingly the Rydberg constant, R, which is proportional to the reduced mass, m^*, is somewhat different for the H, D, and He^+ spectra. While the value in the wave number scale (ν/c) for infinitely heavy nuclear mass is $R = 109737.4$ cm^{-1}, $R_H = 109677.7$ cm^{-1}, and $R_D = 109707.5$ cm^{-1}. For the red α-line of the Balmer series, which corresponds to the transition from $n = 3$ to $n = 2$ and is of frequency $\frac{5}{36} R$ as given by Equation (13), we obtain $\nu_H/c = 15233.01$ cm^{-1} and $\nu_D = 15237.15$ cm^{-1} (the corresponding wavelengths are $\lambda_H = 6564.69$A and $\lambda_D = 6562.91$A). The splitting is, therefore, $(\nu_D - \nu_H)/c = 4.14$ cm^{-1} or $\lambda_H - \lambda_D = 1.78$A. Compared to the fine-structure splitting of this line, 0.33 cm^{-1} due to electron spin—which has been well attested experimentally—the effect of splitting due to mass differences is large. It forms the basis of a convenient spectrographic method to prove the presence of heavy hydrogen in H–D mixtures. Historically, this was the procedure used in 1932 by Urey, Brickwedde, and Murphy to discover heavy hydrogen.

For heavier nuclei the mass-difference effect quickly becomes smaller, and the fine structure increases. Fine structure splits the resonance line $2p \rightarrow 1s$ for potassium into two lines with wavelengths 7699A and 7664A, while the splitting of these lines due to the different mass numbers 39, 41 of the K isotopes is only 0.0053A. Splitting of such small magnitude is below the limits of observability.

2. Nuclear Motion in the Case of Several Electrons. If several electrons share in giving rise to a spectral term, the accompanying nuclear motion varies according to the phase relations between the electrons. It is intuitively clear that the nucleus remains at rest if two electrons travel the same circular path always at opposite points of the path, and that the nucleus experiences the maximum accompanying motion if the two electrons are always at the same part of the circular path.

Wave mechanics maintains that such a pictorial concept of the phases of electronic motions has no physical meaning. Instead, it introduces the quantitative concept of symmetry of eigenfunctions and exchange degeneracy. The idea of phase relations, however, is satisfactory for a qualitative understanding.

The resulting isotopic effect has been thoroughly studied in the Li^+ spectrum. In the transition $2p \rightarrow 1s$ at 18230 cm^{-1}, or 5490A, the splitting produced between the isotopes of mass 6 and 7 is 0.92 cm^{-1}. To this is added a correction of 0.24 cm^{-1}, as described in subparagraph 1 of this section. Experimental verification of the computed value of 1.16 cm^{-1} is difficult because another effect of the same order of magnitude, the hyperfine splitting, is superposed upon it. However, careful discussion has shown the complete agreement of observation and theory.

3. Exchange Paths. In the Bohr model of the atom, paths exist for the electrons to swing through the nucleus. In wave mechanics, on the other hand, eigenfunctions are applied, i.e., electron cloud density distribution functions, which exhibit a maximum in the neighborhood of the nucleus (S-terms). According to both these conceptions the electron stays very close to the nucleus; for this reason, S-terms are more strongly influenced by the atomic nucleus than all other terms (also, e.g., in hyperfine structure, page 32).

The pure Coulomb interaction between nucleus and electron holds, naturally, only for the approximation that the nucleus can be considered as a charged mass point. If the nucleus has finite extension, say a radius, R, then another force which is not completely known will act on the electron. Consequently, for electron paths which pass through the interior of the nucleus, i.e., S terms, a displacement of the corresponding energy level will result. This displacement increases with increasing radius of the nucleus. Because the nuclear radii increase with increasing nuclear masses, we may expect the appearance of this effect especially in the atomic spectra of the heaviest elements; and because the nuclei of the isotopes of the same element possess different radii as a result of their different masses, the spectral lines for elements with different isotopes will split. In Tl, Pb, and Hg, this splitting is of the order of magnitude 0.05 cm^{-1} to 0.1 cm^{-1}. Schüler and Schmidt studied the splitting in the Sm nucleus and found it to be especially large. For the 5321A line of this element the difference between the lightest ($A = 144$) and heaviest ($A = 154$) isotope is 0.23 cm^{-1}. The difference is anomalously large between the isotopes 150 and 152. This may indicate a faster increase of the nuclear radius when mass number 150 is exceeded.

7. Nuclear Masses and the Rotation Spectrum

In principle, the same effects which occur in atomic spectra should be visible in molecular spectra. Until now, however, no investigations of these effects have been made, for the reason that the study of such phenomena is much easier in the case of atoms. Besides, molecules exhibit isotopic effects of an entirely different order of magnitude so that interest centers on these.

It is well known that the possible energy states of a molecule can be divided into three groups. By far the smallest energy is connected with the excitation of a *rotation term*, in which the whole molecule rotates as a rigid body; the spectral terms (rotation bands) lie in the far infrared region. The energy of the *vibration term*, in which the individual nuclei inside the molecule vibrate relatively to one another, is much larger. The terms which correspond to these states lie in the near infrared. Because a molecule can vibrate and rotate simultaneously, the rotation spectrum is superposed upon the vibration spectrum as fine structure. The third group of terms is the *electron term* for which the electron envelop of the molecule can exist in excited states. The corresponding spectral lines are the analogues of the atomic spectral terms and fall in the visible and ultraviolet region, their excitation requiring the largest energy addition. Since a molecule can also rotate and vibrate, an entire rotation–vibration spectrum is superposed as fine structure for each electronic transition. The rotation and vibration spectra can, therefore, be most conveniently observed spectroscopically in the visible region. Thus, one finds in the molecule, as opposed to the atom, not just a single spectral line but an entire "band system" for every electronic transition.

The possible rotational states of a diatomic molecule are described by the Deslandres term formula†:

$$\nu_J = \frac{\hbar}{4\pi M^* a^2} J(J+1) \tag{15}$$

Here J is the rotational quantum number, i.e., the angular momentum of the molecule measured in units of $\hbar$, a is the distance of both nuclei from each other and M^* is the reduced mass formed from the two nuclear masses:

$$M^* = \frac{M_1 M_2}{M_1 + M_2} \tag{16}$$

The rotation frequencies are inversely proportional to the reduced masses.

Two examples are cited: The molecules which may be formed from the two hydrogen isotopes are H_2, HD, and D_2, with reduced masses of approximately $^1/_2$, $^2/_3$, and 1. Consequently, the D_2 terms are twice as dense as the H_2 terms. In this case the isotopic effect is large and may even be used for a precision measurement of the mass of the deuteron.

In the case of hydrogen chloride, HCl, four different types of molecules occur: $^1H\,^{35}Cl$ with $M^* = 0.9799$, $^1H^{37}Cl$ with 0.9813, $^2D\,^{35}Cl$ with 1.9050, and $^2D^{37}Cl$ with 1.9106. The replacement of light by heavy hydrogen leads again to a large effect, while the isotopic effect of the replacement of one chlorine isotope by another contributes only 0.15%. The study of rotation spectra, therefore, is not suited for a precision determination of the masses of heavy nuclei.

8. Nuclear Masses and the Rotation Vibration Spectrum

The frequency with which the two nuclei of a diatomic molecule vibrate depends, of course, on the nuclear masses. According to a very general theorem of mechanics, the vibration frequency of a system is inversely proportional to the square root of its mass. Thus:

$$\nu_2/\nu_1 = \sqrt{M_1^*/M_2^*} \tag{17}$$

if the two indices refer to two molecules, obtained from each other by replacing one isotope by another isotope. The effect in the vibration spectrum is weaker than in the rotation spectrum where, according to Equation (15) above, the relationship is:

$$\nu_2/\nu_1 = M_1^*/M_2^* \tag{18}$$

On the other hand the absolute values of ν for vibration are much larger than those for rotation. The frequencies of a rotation band belonging to the same vibrational transition will merely appear slightly displaced because of the somewhat different positions of the vibration frequencies. The rotation isotopic effect is too small to be measured because the rotation is itself only a "fine structure" of the vibration.

As an example, consider the HCl band which belongs to the transition for which the vibration quantum number, v, changes by one unit. It lies near the wavelength $\lambda = 3.46\mu$ and can be observed in absorption up to rather high values of J. The splitting between

† The rotation energy is equal to the square of the angular momentum, $\mathbf{d}$, divided by twice the moment of inertia: $E_J = \mathbf{d}^2/(2\,M^*a^2)$. According to quantum theory, $E_J = 2\pi\hbar\,\nu_J$ and $|\mathbf{d}| = \hbar J$. The fact that $J(J+1)$ and not J^2 is written in Equation (15) is connected with the statistical nature of quantum mechanics (see footnote, page 28).

wavelength λ_1 belonging to H ^{35}Cl and λ_2 belonging to H ^{37}Cl is, according to Equation (17):

$$\lambda_2 - \lambda_1 = \left(\sqrt{\frac{M^*}{M_1^*}} - 1\right)\lambda_1 = 0.00077\lambda_1$$

This means that for $\lambda_1 = 3.46\mu$, each H ^{35}Cl line is displaced from the H ^{37}Cl line by about $0.0027\mu = 27$A.

The first measurement of this vibrational isotopic effect was made by Imes in 1919 and was interpreted by Loomis and also by Kratzer in 1920. The measurements were made on the "upper band," the center of which lies at 1.76μ and which is easily accessible to measurement. It corresponds to a jump of two units in the vibration quantum number, v. This is not forbidden because the vibrations are not strictly harmonic. (Hence, the upper band does not lie at exactly half the wavelength of fundamental band 3.46μ, i.e., at 1.73μ.) The splitting 13.5A in the upper band is, naturally, only half as large as in the fundamental band. The accompanying line (Fig. 8) at this distance from the principal lines is approximately $^1/_3$ as intense as the principal lines. From this the relative frequencies of the two chlorine isotopes can be estimated as ^{35}Cl:^{37}Cl = 3:1. This agrees well with the more exact present ratio of 3.07.

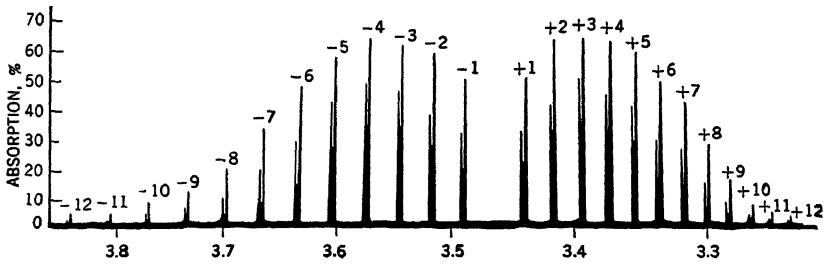


FIG. 8. The vibration isotopic effect in the absorption spectrum of HCl between 3.3 and 3.8 μ.

In general this isotopic effect also is not very marked. Here again, hydrogen is an exception. In the transition from HCl to DCl the fundamental band moves from 3.46μ to 4.8μ. Hardy, Barker, and Dennison measured the rotation structures of both these bands with great accuracy and, using these measurements, made the first precision determination of the mass of the heavy hydrogen isotope (1932). To be sure, for such a precision measurement a term formula is needed which also considers finer effects, such as (*1*) the changes of nuclear distance with increasing rotation quantum number because of centrifugal force; (*2*) the coupling of rotation and vibration which arises from the fact that a change in the average nuclear distance affects the vibration frequencies; (*3*) the anharmonicity of the vibrations which must be taken into account using a suitable potential law with a sufficient number of adjustable constants. The determination gave for the ratio of the reduced masses of H ^{35}Cl and D ^{35}Cl:

$$M_1^* : M_2^* = 0.514430 \pm 0.000004$$

If we take the value of the hydrogen atom to be 1.00813 we obtain for the neutral deuterium atom the value 2.0144 ± 0.0001. This value does not agree within the limits of error with the mass-spectrographic value of 2.014726 ± 0.000008 (Mattauch and Bönisch). From the given limits of error, one sees that even in this most favorable case band-spectroscopic mass determinations are far from capable of attaining the accuracy of mass-spectrographic

methods. Historically, to be sure, band spectroscopy made noteworthy contributions—the rare isotopes of carbon (^{13}C), of nitrogen (^{15}N), and of oxygen(^{17}O and ^{18}O) were discovered by these methods in the years 1929 to 1931.

D. Relative Abundance and Atomic Weight

9. Chemical and Physical Mass Scales

The determination of the relative abundances of the three oxygen isotopes is of fundamental importance for the conversion of the values of atomic weight determined by physical methods (such as isotope research) to the chemical values. The unit of the physical atomic weight scale is the mass of the neutral oxygen isotope, $16:^{16}O = 16$. The historically older chemical scale takes the mass of the mixture of all three isotopes, 16, 17, and 18, as basic and sets it equal to 16. The chemical scale suffers from the drawback that it assumes a constant mixing ratio for the three isotopes. It is fundamentally, therefore, not sharply defined; but the possible uncertainty which enters is so small that it is entirely unimportant for the restricted accuracy that chemistry demands.

The oxygen isotope of mass 17 is of only secondary importance in the conversion from one scale to another. The relative occurrence of ^{17}O and the main isotope ^{16}O is 1:2500. ^{17}O is five times as rare as the ^{18}O isotope, which produces the difference between the two scales. The accompanying table lists the measurements made until now on the abundance of ^{18}O:

Year	Author	Method	Ratio $^{16}O:^{18}O$
1931	Mecke and Childs	Atmospheric bands	610 ± 20 (individual measurements between 430 and 710)
1932	Aston	Mass spectrography	535
1934	Smyth	Mass spectrography	503 ± 10

Smyth's value should be considered as the best which exists so far. No good recent determination of the abundance of ^{17}O is available. Without great error, however, a 20% leeway may be allowed: $^{16}O:^{17}O = 2500 \pm 500$. With this value and the ^{18}O abundance value of Smyth, we obtain the conversion factor:

$$\text{Physical atomic weight} = (1.000275 \pm 0.000007)\cdot\text{chemical atomic weight} \quad (19)$$

The calculation of chemical atomic weights from the results of physical isotope research, as they are given in the appended tables, is made in the following way: First, the *average mass number* of the element in question is calculated by multiplying the mass number of each isotope by its relative abundance and adding the products. The packing fraction is then brought in as a correction to this average mass number and the atomic weight in the physical scale is obtained. It is assumed in this calculation that all isotopes of the same element have the same packing fraction. With the exception of the better-known lightest elements up to approximately mass 40, this condition is completely fulfilled within the limits of accuracy of measurement. For the lighter nuclei the concept of average mass number is not introduced, but the individual masses are multiplied by their abundances and the products are added. In any case, the conversion to the chemical scale is made with the help of Equation (19) in order to compare the calculated value with chemical results.

An example of the practical procedure is given: Strontium has isotopes 84, 86, 87, 88 with relative abundances as indicated in the accompanying table. The third column of the table contains the product of the mass number by the frequency of occurrence, expressed in terms of a sum. Beneath this the sum, i.e., the average mass number, is written:

Mass number	Abundance	Product
84	0.56%	(88 − 4)·0.0056
86	9.86%	(88 − 2)·0.0986
87	7.02%	(88 − 1)·0.0702
88	82.56%	88 ·0.8256
Average mass number: 88 − 4·0.0056 − 2·0.0986 − 1·0.0702 = 88 − 0.2898 = 87.7102		

The fourth decimal is very uncertain and may be neglected. This average mass number should be corrected with the packing fraction, $-6.9 \cdot 10^{-4}$ MU, and Smyth's denominator, 1.000275. The atomic weight of strontium in the chemical scale is, therefore:

$$87.710 \cdot (1 - 0.00069 - 0.000275) = 87.710 \cdot (1 - 0.00097) = 87.710 - 0.085 = 87.625$$

Corresponding to the limits of error, this may be rounded off to two decimals: 87.63. This agrees completely with the chemical value of 87.63.

10. Limits of Constancy of Relative Abundance

Since the discovery of isotopy, physicists have tried to obtain pure isotopes in weighable amounts or at least to concentrate the isotopic content of a given isotope in an element. Theoretically, the methods of mass spectrography are suitable for this purpose. However, these methods yield very small quantities and even with the most modern "strong intensity" mass spectrographs, which are built especially for this purpose, hardly more than several tenths of a milligram of a pure isotope can be obtained after weeks of operation.

Theoretically, most processes in nature are dependent on the masses of isotopes and are, therefore, associated with the concentration of individual isotopes: Diffusion processes, evaporation, electrolysis, chemical reactions, photochemical transformations show a certain dependence on the isotope mass. However, in every case the effect is extremely small, with the single exception of hydrogen, where one isotope is twice as heavy as the other. For example, the first traces in the evaporation process exhibit a slight excess of lighter atoms. However, if an appreciable amount is evaporated, heavy atoms will also evaporate and the concentration of light atoms decreases. The unevaporated residue becomes richer in the heavy isotope, but if one wants to obtain a considerable concentration, one is left with only a small quantity of unevaporated material. The situation is the same with all other separation processes. Even though the chemical elements have passed through countless evaporations, chemical reactions, and diffusion processes since the formation of the earth, almost no noticeable effects could have resulted.

The enrichment of large quantities of an isotope, now technically possible, uses a large number of "separating units" connected to one another. Of course, each unit gives only a small effect, but all together produce perceptible results. This "multiplication phenomenon" is very unlikely to occur in the processes of nature.

In recent years observations of increased accuracy have divulged slight fluctuations in the relative abundance of the isotopes of natural elements. In 1939 Nier and Gulbransen investigated carbon dioxide from different sources in the mass spectrograph and found fluctuations up to 5% in the abundance ratio $^{12}C:^{13}C$. The heavy isotope appeared to be

favored in limestone, the light one in plants, and an average value was obtained for air. Brewer investigated samples of potassium in 1936. The ratio $^{39}K:^{41}K$ was constant at 14.20 for ocean water of different origin and depth, but the composition of mineral potassium varies between 14.1 and 14.6, and that obtained from the ashes of plants between 12.6 and 14.6. For hydrogen, the values of the abundance ratio $^{1}H:^{2}H$ given by individual authors exhibit larger differences than are compatible with the limits of error (between 5000 and 6000).

These fluctuations have a certain importance in pure physics in connection with the standardization of the atomic weight scale with the help of the abundances of the oxygen isotopes (page 17).

The abundance fluctuations in lead have a different cause and are of a different order of magnitude.

E. Nuclear Spin

11. Concept of Spin

We know that the electron possesses an intrinsic angular momentum of value $^1/_2\hbar$ which is usually called "spin." This can be understood *qualitatively* by picturing the electron as a charge cloud, the radius of which is approximately:

$$\frac{e^2}{mc^2} = 2.81 \cdot 10^{-13} \text{ cm} \tag{20}$$

and which rotates about its own axis. This conception has proved to be *quantitatively* incorrect since the circular current loop connected with the revolving charge produces a magnetic moment of magnitude $(e/mc) \cdot {}^1/_2\,\hbar$. Actually the spin is related to a magnetic moment*:

$$\frac{e}{mc}\frac{1}{2}\hbar = 0.922 \cdot 10^{-20} \text{ gauss cm}^3 = 1 \text{ Bohr magneton} \tag{21}$$

The Dirac theory showed later that the correct spin and magnetic moment of the electron are obtained as a consequence of the relativistic equations of motion.

If the motion of the heavy particles (neutron and proton) could be described by equations which were constructed completely analogously to the Dirac equations for the electron, each particle would have spin $^1/_2\,\hbar$. Their magnetic moments would, however, be different: While the proton would have a moment:

$$\frac{e}{Mc}\frac{1}{2}\hbar = 0.502 \cdot 10^{-23} \text{ gauss cm}^3 = 1 \text{ nuclear magneton} = 1 \text{ NM} \tag{22}$$

that of the neutron would have to be zero. Neither of these conditions is realized. According to the most exact present-day values, the magnetic moment of the proton is $\mu_p = +2.78$ NM and that of the neutron is $\mu_n = -1.94$ NM. This complexity of the results compared with the theory of the electron appears to be related to the possibility of transformation of proton and neutron into each other through radioactive β-decay (see page 85). In this process the idea of elementary particles loses its original exactness and becomes indefinite.

* 1 gauss cm^3 = 1 e. s. u. cm. Multiplication by a magnetic field strength in gauss gives an energy in ergs.

We therefore redefine: We shall call electron, proton, and neutron "elementary particles" without attributing deeper meaning to this idea. This definition would be meaningless within the present status of physics. The following rules then hold:

1. Elementary particles have spin $^1/_2\,\hbar$.
2. Elementary particles obey the Pauli principle and hence Fermi statistics.

The Pauli principle maintains that the wave mechanical eigenfunction is antisymmetric, i.e., an exchange of two identical particles changes its sign. In this case it is not possible for two particles to be in the same state, since exchanging the two would convey the eigenfunction into itself, i.e., its sign could not change. This circumstance governs the structure of the electron shells of the atom and is the real foundation of chemistry. Since the Pauli principle is also to be fulfilled for protons and neutrons, the structure of atomic nuclei is also governed by it. The application of this principle to systems with very many particles leads, as a consequence of the impossibility of putting two particles into the same quantum state to a modification of classical statistics which is called Fermi statistics. Proton and neutron, therefore, obey Fermi statistics.*

Structures which are formed from several elementary particles as, e.g., atomic nuclei, when viewed as a single entity, do not need to obey Fermi statistics. Let us consider a system consisting of two deuterons, hence of two protons, P_1 and P_2, and two neutrons, N_1 and N_2. Then the eigenfunction should change sign for an exchange of P_1 and P_2, as well as for an exchange of N_1 and N_2, since the Pauli principle holds for protons as well as for neutrons. In order to exchange both deuterons entirely it is evidently necessary to carry out the two exchanges one after the other so that two changes of sign result. The eigenfunction is, therefore, invariant with respect to an exchange of the two deuterons, or as usually expressed, it is symmetric in both deuterons. Consequently, Fermi statistics do not hold for deuterons, but, instead, Bose statistics, permitting an accumulation of arbitrarily many particles in the same quantum state.

We can immediately generalize the foregoing consideration by making the following statement: A system consisting of an even number of elementary particles obeys Bose statistics independently of whether all these elementary particles are of the same type. If the system consists of an odd number of elementary particles, it obeys Fermi statistics. An exchange of two such systems changes the sign an even number of times in the first case, an odd number of times in the second case. In the first case the sign is, therefore, preserved, while in the second it is not.

* Physical statistics are based upon the following hypothesis: If n different particles can be distributed over N different states in different ways, then all distributions for prefixed n and N are equally probable. Here we mean by states a specification of a region of volume, h^3, in a "phase space," the coordinates of which are the three momentum and position coordinates of the particles. Quantum statistics modify the probability concept somewhat, by maintaining that there is no way of distinguishing between identical particles so that all states of the entire system which arise from each other only by exchange of identical particles, are to be counted as a single state. This revised method of counting of equally probable states is common to the Bose and Fermi statistics. Fermi statistics, in addition, must fulfill the Pauli principle: Two particles may not be in the same cell of volume h^3 in phase space. The fact that both types of quantum statistics are equally satisfactory forms is best seen by considering eigenfunctions. For particles which obey Fermi statistics these must be antisymmetric with respect to exchanges, while for particles obeying Bose statistics they must be symmetric. The fact that such a symmetry requirement exists follows from the new method of counting. States which differ in the exchange of two particles have the same eigenfunction and are therefore not considered as separate in the counting. Of the two possible properties of symmetry and antisymmetry, the latter obtains clear meaning by means of the Pauli principle. The first is difficult to understand intuitively.

If the validity of Fermi statistics for protons and neutrons has been shown, the statement can be made in the following way: Atomic nuclei of even mass number obey Bose statistics, while nuclei of odd mass number obey Fermi statistics. The nucleus ^{14}N must, therefore, obey Bose statistics, a statement which has been confirmed experimentally (page 25). At the same time, the old idea that a nucleus of mass number A and charge number Z consists of A protons and $(A - Z)$ electrons has been contradicted. For, according to this older conception, the ^{14}N nucleus would consist of 21 particles, i.e., an odd number, and so should obey Fermi statistics.

12. Nuclear Spin from the Rotation Spectrum

In the following we shall consider diatomic molecules with two equal nuclei (homonuclear). The state of such a molecule is completely described by the following information: The molecule as a whole carries out a rotation in space with an angular momentum $\hbar J$ ($J = 0, 1, 2 \ldots$ rotational quantum number). The direction of this rotation in space is determined by the quantized value of the angular momentum component in a given direction (magnetic quantum number, m). Because of this rotational motion, the instantaneous direction of the line connecting the two nuclei can be described by two polar angles, θ and φ. Both nuclei vibrate with respect to each other with vibration quantum number $v(v = 0, 1, 2 \ldots)$, the coordinate describing this motion being the distance r_{12} of the two nuclei from each other. Both nuclear spins $\mathfrak{s}_1$ and $\mathfrak{s}_2$ (each of magnitude $i\hbar$) can set themselves in different directions with respect to the other, so that the total nuclear spin can take the values $s = 2i, 2i - 1, 2i - 2, \ldots$ Finally, the electron envelop is in a definite state which can be described by the eigenfunction, Φ, of the electron coordinates and electron spin. The total eigenfunction of the molecule has the form:

$$\Psi = \psi_{J,m}(\theta, \varphi) u_v(r_{12}) \chi(\mathfrak{s}_1, \mathfrak{s}_2) \Phi$$

The rotation eigenfunction, $\psi_{J,m}$ is a spherical harmonic. It is symmetric with respect to interchange of both nuclei when $J = 0, 2, 4 \ldots$ is an even number; i.e., it does not change sign when this interchange is made. On the other hand, it is antisymmetric, i.e., it changes sign upon exchange if $J = 1, 3, 5 \ldots$ is odd. u_v depends only on the distance r_{12} of the two nuclei from each other. Since this distance is unchanged with change of the two nuclei, u_v is symmetric with respect to exchange. The following rule holds for the "spin function": For values $s = 2i, 2i - 2, \ldots 0$ of the total spin, χ is symmetric, while for values $s = 2i - 1, 2i - 3, \ldots, 1$ it is antisymmetric with respect to exchange. The electron eigenfunction, Φ, is also not independent of exchange. It can be either symmetric or antisymmetric.

The number of different possible combinations of the two nuclear spins to form a total spin, s, is $2i + 1$. Each total spin, s, has, in addition, a statistical weight, $2s + 1$, corresponding to the possibility of existing in $2s + 1$ directions, with different quantized components in a fixed direction (direction quantization). Thus, the table on page 22 is obtained.

On the basis of this table we shall discuss some individual cases. Let us begin with nuclei with no spin ($i = 0$). As the table shows, only symmetric spin functions are realized. This case is trivial, χ simply $= 1$. If both nuclei satisfy Bose statistics, the total eigenfunction, Ψ, must, in any case, be symmetric with respect to an exchange of both nuclei. Since u_v and χ are symmetric, ψ must also be symmetric in the case of a symmetric electron

i	$2i+1$	s	Symmetry of χ	$2s+1$	Ratio of statistical weights, anti./symm.	Examples
0	1	0	symmetric	1	0:1	He_2, C_2, O_2, S_2
$^1/_2$	2	0 1	antisymmetric symmetric	1 3	1:3	H_2, F_2
1	3	0 1 2	symmetric antisymmetric symmetric	1 3 5	1:2	D_2, N_2
$^3/_2$	4	0 1 2 3	antisymmetric symmetric antisymmetric symmetric	1 3 5 7	3:5	$^4Li_2$
2	5	0 1 2 3 4	symmetric antisymmetric symmetric antisymmetric symmetric	1 3 5 7 9	2:3	
$^5/_2$	6	0 1 2 3 4 5	antisymmetric symmetric antisymmetric symmetric antisymmetric symmetric	1 3 5 7 9 11	5:7	Cl_2

state, Φ, i.e., only even rotation quantum numbers, $J = 0, 2, 4, \ldots$ enter. On the other hand, only odd $J = 1, 3, 5, \ldots$ come into play in the case of an antisymmetric electron state, Φ. Therefore, in the rotation spectra of these molecules every second line is absent. In this manner it could be shown experimentally that the nuclei ^4He, ^{12}C, ^{16}O, and ^{32}S have no nuclear spin. From the fact that in these nuclei even J is associated with the symmetric electron terms, one could also conclude that they obey Bose statistics.

The relations are somewhat more complicated if nuclear spin is present. Consider the case $i = {}^1/_2$, realized in the hydrogen molecule. If both spins are parallel so that $s = 1$, χ is symmetric and we have the state which is called orthohydrogen. It has a statistical weight 3, corresponding to the three orientation possibilities of s with components 1, 0, -1 in a given direction. In the case of antiparallel spin $s = 0$, and we have parahydrogen with a statistical weight 1. No transitions between these two types are possible. Thus, we are concerned with two entirely different types of hydrogen, which are present in hydrogen in amounts corresponding to their statistical weights, 1:3. This mixing ratio can be inferred not only experimentally from the rotation spectrum, but also, e.g., from the specific heat of hydrogen (page 26). The spectrum shows that not only do the rotation terms exhibit a characteristic intensity change corresponding to the weight ratio 3:1, but also that the even J are related to the smaller statistical weight. Inasmuch as the ground state of the electron configuration is symmetric with respect to nuclear exchange, this means: For symmetric ψ, χ is antisymmetric and Φ symmetric, thus Ψ is antisymmetric and, consequently, *hydrogen nuclei obey Fermi statistics.* This statement is extremely important for nuclear physics, because it concerns one of the fundamental properties of the proton.

These considerations may be applied to heavy hydrogen, which does not differ from light hydrogen so far as the electron state is concerned. Here again, the electron eigenfunction of the ground state, Φ, must be symmetric. The even rotation quantum numbers are, however, now related to the larger statistical weight in the spectrum. In fact, they have twice as large a weight as the odd J. According to the table, it follows from this weight ratio 2:1 that the nuclear spin of the deuteron is $i = 1$. If one correlates the more

frequent state in which the nuclear spin is symmetric, with the symmetric rotation terms with even J of symmetric electron eigenfunction, Φ, it follows that the total eigenfunction, Ψ, is also symmetric. Thus, deuterons obey Bose statistics.

13. Nuclear Spin from the Raman Spectrum

Suppose monochromatic light (say the mercury resonance line, 2537A) is sent into a gas, e.g., oxygen. Then besides the coherent scattering of light preserving its original frequency, we observe incoherent scattering giving rise to the Raman lines. Under the action

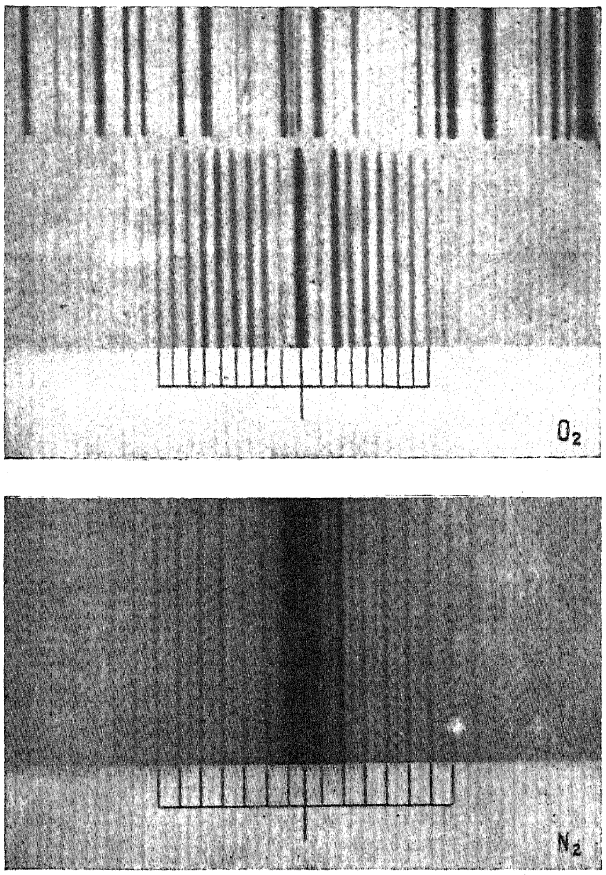


FIG. 9. Change of intensity in the Raman rotation spectrum, according to Rasetti. At the upper edge of the oxygen illustration, a comparison spectrum is shown.

of a light quantum, an O_2-molecule goes into a higher energy state and in this scattering process the light quantum gives up part of its original energy. Scattered light of lower frequency therefore results (Stokes lines). On the other hand, if the molecule was already in an excited state, it can, under the influence of the light quantum, go into a lower state. The scattered light is then of higher frequency than the original (anti-Stokes lines). At normal temperature many rotation terms are thermally excited originally, hence both types

of lines occur. They form a spectrum about the introduced line (Raman rotation spectrum).

The central line of this spectrum, containing the entire coherent scattered intensity, naturally possesses a greater intensity than the incoherent neighboring lines. Thus, danger of an overlapping onto the nearest neighbors exists, as Figure 9 shows for nitrogen. Rasetti used the idea here of sending the scattered light again through mercury vapor. The central line, which has the frequency of the mercury resonance line, is strongly absorbed while the scattered light passes through practically unweakened. The case of O_2, reproduced also in Figure 9, shows the success of this method.

In order to study both these illustrations, notice that in the Raman rotation spectrum the selection rule $\Delta J = \pm 2$ or 0 holds. The transition $\Delta J = 0$ leads only to the undisplaced central line. Those frequencies for which the molecule goes from the lower state J to the higher $J' = J + 2$ can be calculated from Equation (15). These are the Stokes lines:

$$\nu = \nu_0 - \frac{\hbar}{4\pi I}(4J + 6) \qquad (J = 0, 1, 2, \ldots)$$

If the molecule goes from the higher state J (J at least 2) to the lower $J' = J - 2$, the anti-Stokes lines result, with frequencies:

$$\nu = \nu_0 + \frac{\hbar}{4\pi I}(4J - 2) \qquad (J = 2, 3, 4, \ldots)$$

In the accompanying table, the frequency displacements, $\nu - \nu_0$, for the lowest J values are written in units $\hbar/4\pi I$.

	Transition $J \rightarrow J'$	$\nu - \nu_0$	Intensities for	
			O_2	N_2
Stokes Lines	$4 \rightarrow 6$	-22	0	2
	$3 \rightarrow 5$	-18	1	1
	$2 \rightarrow 4$	-14	0	2
	$1 \rightarrow 3$	-10	1	1
	$0 \rightarrow 2$	-6	0	2
Anti-Stokes Lines	$2 \rightarrow 0$	$+6$	0	2
	$3 \rightarrow 1$	$+10$	1	1
	$4 \rightarrow 2$	$+14$	0	2
	$5 \rightarrow 3$	$+18$	1	1
	$6 \rightarrow 4$	$+22$	0	2

For oxygen, every second line does not appear in the observed spectrum. The distances of the first and second lines from the center are not in the ratio 6:10, but 10:18, corresponding to the presence of only odd J. (If only even J were present, the ratio would have to be 6:14). From the absence of every second line it follows that the nuclear spin of ^{16}O is $i = 0$. According to the considerations on page 21, the spin eigenfunction is in this case symmetric with respect to nuclear exchange. The rotation eigenfunction is antisymmetric since J is odd. Furthermore, the electronic ground state of the O_2-molecule is known to be antisymmetric with respect to a nuclear exchange. Thus, as a whole, the permitted states of the O_2-molecules are symmetric in the nuclei, i.e., ^{16}O nuclei obey Bose statistics.

In nitrogen no lines are absent, but the terms with even J have double the statistical weight of those with odd J. According to the table on page 22, this ratio 2:1 gives a nuclear spin $i = 1$ for ^{14}N; the terms with even J are related to the symmetric nuclear spin

eigenfunction. Besides this, the electron ground term of nitrogen is symmetric in the nuclei, so that ^{14}N-nuclei obey Bose statistics. This conjecture was first made by Heitler and Herzberg in 1929 on the basis of Rasetti's picture. It leads, as seen on page 21, to a contradiction of the old representation according to which nuclei are considered made up of protons and electrons, but it is in agreement with the idea of formation from protons and neutrons in which neutrons as well as protons must satisfy Fermi statistics.

14. Nuclear Spin from Rotational Energy

Classical physics maintained that every diatomic molecule possesses five degrees of freedom, three translational and two rotational. The molecule was treated as a rigid body, and rotation about the line joining the nuclei was not regarded as a degree of freedom. According to the law of equipartition, each degree of freedom was assigned an average energy of $^1/_2\, kT$. From this the molar heat was obtained, i.e., the temperature derivatives of the energy content, U, of a mole of the substance:

$$C_v = \frac{\partial U}{\partial T} = L\frac{\partial}{\partial T}\left(\frac{5}{2}kT\right) = \frac{5}{2}R \tag{23}$$

(L = Loschmidt number, R = gas constant). It was soon shown that this formula fails for hydrogen at low temperatures. The deviation from the formula increases with decreasing temperature and the results obtained for the molar heat are less than those given by Equation (23).

From the theoretical point of view it appears strange that the molecule is conceived of as a rigid body, because we know that it contains a group of electrons besides the two nuclei. In the limiting case of high temperatures the molecules not only dissociate into atoms, but the atoms themselves also ionize. Then the numerous degrees of freedom of the electrons, as well as the six degrees of freedom of the two nuclei, enter. The consistent application of classical physics demands the same large number of degrees of freedom at arbitrarily low temperatures, for even then, for example, electrons could vibrate in the molecule with average energy of $^1/_2\, kT$. At low temperatures the vibrations would simply be very small.

At this point the modification due to quantum theory enters. So long as one deals with gases, the classical conceptions with regard to the translational degrees of freedom are left unchanged. Quantum theory demands, however, that the rotational and internal degrees of freedom be quantized. If, in a molecule, the only energy levels possible for these degrees of freedom are E_0, E_1, E_2, ... the molecule will be at the absolute zero point when it is in state E_0. The rotations and vibrations will not be excited at all. With increasing temperature the higher states will be gradually occupied according to the Boltzmann law. The increase in energy content of the substance consists not only of increased kinetic energy of the molecules, but as well of the gradual entrance of certain types of motion, so that the molecules are raised to more and more excited states. The states which are first excited with increasing temperature are those demanding the smallest energy expenditure; these are the two rotations, which are contained also in the classical model. The degrees of freedom of higher energy enter with higher temperatures. Next the vibrations arise and their complete excitation usually leads to dissociation. Electron terms and rotation about the line binding the nuclei correspond to the highest energy levels, in which thermal excitation hardly plays a part.

In general, molar heat is divided into two parts: the translatory, which has the classical value $^3/_2 R$, and the rotational heat, which reaches the classical value R at high temperatures. The energy of a rotation term (see footnote, page 15) is:

$$E_J = \frac{\hbar^2}{2I} J(J + 1) \tag{24}$$

If kT is of the same order of magnitude, the corresponding rotation term is strongly excited. The excitation of the rotation terms with increasing temperature takes place more rapidly if the moment of inertia, I, of the molecule is larger. As a result, the increase in rotation for all molecules besides hydrogen takes place at such low temperatures that observation becomes very difficult. For H_2, $I = 0.47 \cdot 10^{-40}$ g cm^2, as calculated from the distance of the lines in the band spectrum or the Raman spectrum. If one puts $E_J = kT$, one obtains for the critical excitation temperature $T = 85° \, J \, (J + 1)$. Thus, the increases take place over a region of several hundred degrees.

From our standpoint, the rotational heat of hydrogen is of interest because its results concerning classification and the statistical weight of the rotation terms lead to the same conclusions regarding nuclear spin and statistics as the results from the molecular spectrum. Since we are dealing with a pure rotation spectrum and only a single electron and vibration term is present, namely the ground state, the relations here are simple, just as in the Raman spectrum.

For the rotational heat, the formula:

$$C = \frac{R}{(kT)^2} (\overline{E_J^2} - \overline{E}_J^2) \tag{25}$$

is obtained from general thermodynamic considerations. These considerations do not lose their validity in quantum theory. The rotational heat, C, is thus a measure of the average square fluctuations of the rotational energy. The existence of rotational heat is associated with fluctuations of rotational energy, i.e., with quantum jumps between the different rotation terms. If there were only one rotation state, we would have $C = 0$. This is certainly fulfilled for $T = 0$, where the rotational heat must vanish.

The averaging is carried out by means of the formulas:

$$\overline{E}_J = \frac{\sum_J g_J E_J e^{-E_J/kT}}{\sum_J g_J e^{-E_J/kT}} \text{ and } \overline{E_J^2} = \frac{\sum_J g_J E_J^2 e^{-E_J/kT}}{\sum_J g_J e^{-E_J/kT}} \tag{26}$$

where E_J is the rotational energy given by Equation (24) and

$$g_J = 2J + 1 \tag{27}$$

is the statistical weight of the rotation term, J. The increase of rotational heat with temperature may be calculated by using Equations (24) to (27).

We shall first examine the relations in light hydrogen. The gas at room temperature consists of $^3/_4$ of the orthomodification with odd J and $^1/_4$ of the paramodification with even J (see page 22). This high-temperature equilibrium freezes at low temperatures because, in general, no possibility exists for one of these types to change into the other. The decrease of rotational heat at low temperatures must show a form dependent upon the mixing ratio 1:3. Figure 10 illustrates the curves for the following mixtures:

H_2 (J even)/H_2 (J odd)	= 0:1, i.e.,	$i = 0$ and	Fermi statistics
	= 1:0	$i = 0$	Bose statistics
	= 1:3	$i = {}^1/_2$	Fermi statistics
	= 3:1	$i = {}^1/_2$	Bose statistics
	= 1:2	$i = 1$	Fermi statistics
	= 2:1	$i = 1$	Bose statistics

The introduced measured points fall nearly on the curve which corresponds with the ratio 1:3 for $i = {}^1/_2$ and Fermi statistics for protons. This furnishes another proof of these two properties of protons.

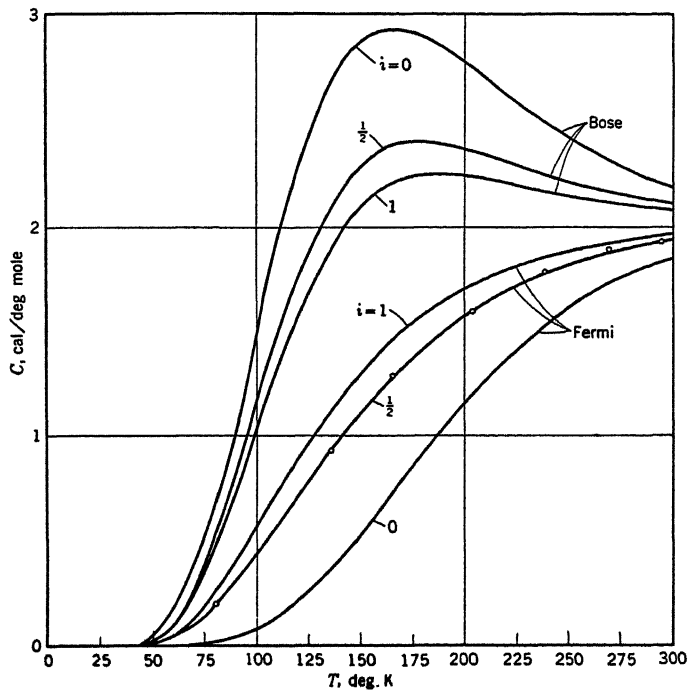


FIG. 10. Rise of rotational heat with absolute temperature in ordinary hydrogen. Curves: theoretical, according to different assumptions about spin, i, and statistics of protons. Circles: measured values by Cornish and Eastmann.

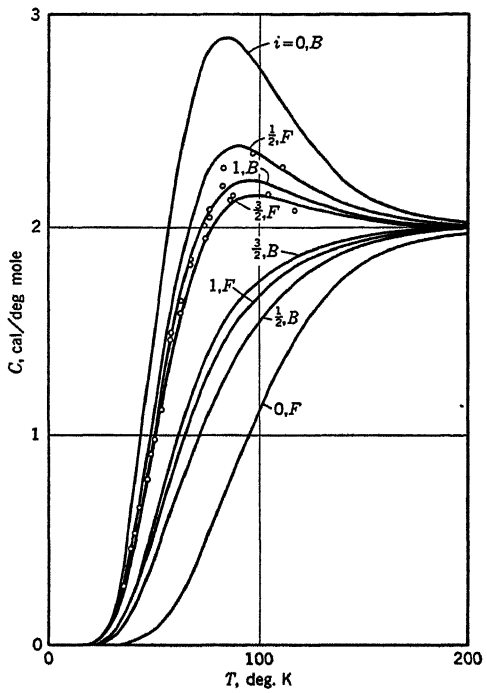


FIG. 11. Rise of rotational heat with absolute temperature in heavy hydrogen. Curves: theoretical, according to different assumptions about spin, i, and statistics (Bose = B, Fermi = F) of deuterons. Circles: measured values by Clusius and Bartholomé.

The experimental procedure can be extended also to the heavy hydrogen molecule D_2. As the moment of inertia is twice as large, the increase in rotational heat takes place in half as large a temperature range as for light hydrogen. The experimental accuracy is consequently strongly reduced. The measured points in this case are compatible also with the expectation that deuterons obey Bose statistics and have spin $i = 1$ (Fig. 11). However, the possibility of spins ${}^1/_2$ and ${}^3/_2$ with Fermi statistics cannot be excluded with certainty on the basis of rotational heat.

F. Nuclear Magnetic Moment

15. Hyperfine Structure

Information concerning the magnetic moments that can be possessed by the atom is most easily obtained by investigation of the *Zeeman effect.* If an atom with a magnetic moment, $\mathfrak{y}$, is brought into an external magnetic field, **H**, an energy level of the atom will be displaced by an amount of energy:

$$\Delta E = -(\mathbf{H} \cdot \mathfrak{y}) \tag{28}$$

The displacement is thus proportional to the component of the magnetic moment in the direction of the field, and because this component is quantized ("magnetic quantum number," space quantization), values of ΔE are obtained depending on its value. This results in a splitting of the original atom term into several. The magnetic moment can easily be determined from the amount of splitting, using Equation (28).

The relations are not so simple for the *fine structure* of the atom terms. In order to see the relations clearly we shall carry out the description with the help of the vector model. Every electron state has a spin, $\mathbf{s}\hbar$, besides its orbital angular momentum, $\mathbf{l}\hbar$, and both possess magnetic moments—an orbital moment in direction **l** and a spin moment in direction **s**. The vectors **l** and **s** must be oriented with respect to each other so that the total angular momentum, $\mathbf{j} = \mathbf{l} + \mathbf{s}$, is also quantized. In case $l > s$, **j** can take the $2s + 1$ different values, $j = l + s, l + s - 1, l + s - 2, \ldots l - s$; if $s > l$, j can have the $2l + 1$ different values, $j = s + l, s + l - 1, s + l - 2, \ldots s - l$. Each of these states corresponds to a somewhat different energy because of the different interaction between the magnetic fields coupled with **l** and **s**. Correspondingly, the term will split into a multiplet with $2s + 1$ or $2l + 1$ components. The magnitude of this splitting can again be calculated with Equation (28), if we now understand by $\mathfrak{y}$ the magnetic eigenmoment of the electron connected with the spin, and by **H** the magnetic field at the position of the electron, this magnetic field being produced by the motion of the electron. This holds at least as long as the term arises from the motion of a single electron. It is seen, however, that even then a quantitative calculation of the magnetic moment demands at least a knowledge of the eigenfunction.

Some important rules may easily be cited without carrying out this calculation completely. First of all, we already know the number of components in a multiplet, $2s + 1$ (for $s < l$) and $2l + 1$ (for $l < s$). Besides this, the *interval rule* for the relative separation of the components must hold: The interaction energy, ΔE, must be proportional to the scalar product of both magnetic moments. Thus, we get for the cosine of the angle between **l** and **s**:

$$\cos(\mathbf{l}, \mathbf{s}) = \frac{l^2 + s^2 - j^2}{2\,sl} \tag{29}$$

Quantum mechanics, which always puts expressions of the form $j(j + 1)$* in place of the

* Intuitively, this means: *Quantum numbers are averages* over time intervals which are so long that the atomic system can traverse very many periods of the paths in this time. If the measurements are of only short duration, every value of the angular momentum will be observed. There is, however, an essential indeterminacy which is so large that one cannot decide whether the angular momentum is integral or not. Strictly speaking, the average value of j^2, i.e., $\overline{j^2}$, and not the square of the average value of j, i.e., $\bar{j}^2$, must be taken in our formula. According to the statistical formula for the average square deviation:

$$j^2 - \overline{j^2} = \bar{j} \text{ or } \bar{j}(\bar{j} + 1) = \bar{j}^2$$

square of the angular momentum quantum numbers, changes this formula somewhat. Within a given multiplet, s and l are the same numbers. Hence, inside a multiplet:

$$\Delta E = C_{l,s}[l(l+1) + s(s+1) - j(j+1)] \tag{30}$$

where $C_{l,s}$ is a constant dependent on the absolute value of the moment and on the eigenfunctions, i.e., on s and l, but independent of j.

The relationships of the *hyperfine structure* (H.F.S.) are entirely analogous to those of the fine structure. If the atomic nucleus possesses a magnetic moment, this moment can interact with the total magnetic moment of the electron envelop which is coupled with the vector, **j**. Nuclear moments are of an order of magnitude 1000 times as small as those in the envelop; consequently, the resultant splitting will be 1000 times smaller than that of ordinary fine structure. In order to observe hyperfine splitting, the natural Doppler width of spectral lines must be eliminated by working at low temperatures. In this way Schuler, in 1928, observed for the first time a hyperfine splitting in the Na D-lines. The normal fine structure of the sodium resonance line effectively splits it into the doublets 5890A ($3\ ^2P_{1/2} \rightarrow 3\ ^2S_{1/2}$) and 5896A ($3\ ^2P_{3/2} \rightarrow 3\ ^2S_{1/2}$). These are just the two D-lines; the difference of 6A is the fine structure. A hyperfine structure should thus be about 0.01A. The observed splitting of 0.02A actually falls within this order of magnitude.

The analogy between the fine structure and the hyperfine structure is perfect. The nuclear spin, **i**, and the total angular momentum, **j**, of the electron cloud can be joined in different ways to form a total angular momentum, **f**. We present the following comparison:

FINE STRUCTURE	HYPERFINE STRUCTURE
Coupling of orbital moment, **l** and electron spin, **s** gives the result	Coupling of electron moment, **j** and nuclear spin, **i** gives the result
$\mathbf{j} = \mathbf{l} + \mathbf{s}.$	$\mathbf{f} = \mathbf{j} + \mathbf{i}.$
The term splits into $2s + 1$ components, if $l > s$; $2l + 1$ components, if $s > l$.	The term splits into $2i + 1$ components, if $j > i$; $2j + 1$ components, if $i > j$.
The displacement ΔE of a component is proportional to $j(j+1) - l(l+1) - s(s+1)$ (interval rule).	The displacement ΔE of a component is proportional to $f(f+1) - j(j+1) - i(i+1)$ (interval rule).

These rules are frequently sufficient for the determination of the nuclear mechanical moment, i.e., the spin. Often, they may be very valuably supplemented by the intensity rules. If we examine the hyperfine structure components of the identical fine structure line (n, j) (n', j'), the sums of the intensities of all the lines arising from transitions between a fixed state, f, and different states, f', are related as the statistical weights $(2f + 1)$ of their initial states. Inversely, the sums of the intensities of the lines going from all f to a fixed f' are related as the statistical weights $(2f' + 1)$ of their final states. These two rules do not suffice to calculate the intensities of all components, but they give very important information. To complete them, the selection rule $\Delta f = 0, \pm 1$ is necessary.

Especially important is the fact that the absolute magnitude of the hyperfine splitting of an S-term is always much greater than that of other terms. This derives from the splitting resultant upon the interaction of nucleus and electrons, and from the fact that for an S-term (corresponding to a "pendulum orbit" in the Bohr model), the eigenfunction is

larger near the nucleus, i.e., more often than for any other term, the electron is found close to the nucleus.

EXAMPLE: Consider the H.F.S. of sodium, mentioned above. Each of the two resonance lines, D_2 and D_1, splits into a doublet. According to the very exact measurements of Granath and Van Atta, the intensity relation 5:3 holds for the two components of each doublet. This splitting arises from the ground term $3\ ^2S_{1/2}$, common to both lines. As $j = {}^1/_2$, two components must result, independently of the magnitude of the nuclear spin, so long as a nuclear magnetic moment does exist. Thus, in this case, it is fundamentally impossible to determine the nuclear spin from the number of components. We can, however, calculate the intensity ratio of the two doublet components for a given nuclear spin i, using the second intensity rule. Since, certainly, $i \geqq j$, there are two terms with $f = i + j$ and $f = i - j$ in the ground state with statistical weights $2(i + j) + 1$ and $2(i - j) + 1$. The intensity ratio must, therefore, become:

$$\frac{2(i + j) + 1}{2(i - j) + 1} = \frac{i + 1}{i}$$

From the observed value 5:3, we obtain $i = {}^3/_2$. Of course, a rather exact determination of the intensity ratio is needed to fix the nuclear spin. As a result, wrong conclusions have often been drawn using this method, especially because the intensities in the experiment are easily falsified by unequally strong self-absorptions of the two components.

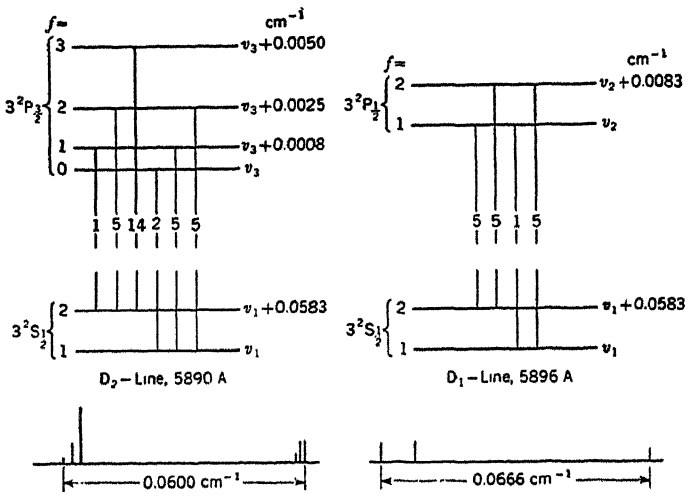


FIG. 12. Hyperfine structure of the two D-lines of sodium. Term scheme and line diagram.

The complete term scheme and line diagram of the H.F.S. of the two Na D-lines are given in Figure 12. The much smaller splitting of the P-terms can be concluded only indirectly. The splitting of the D_2-line at 5890A. is 0.0555 cm^{-1}, deviating from that of the D_1-line at 5896A (0.0612 cm^{-1}). Inasmuch as the S-term is the same in both cases, this difference must arise from the P-term. Granath and Van Atta's values are entered in the diagram. But they also used the theoretical conclusion, not yet tested experimentally, that the splitting of both P-terms is in the ratio 3:5. This follows from the formula which will be derived later (Eq. 31).

In order to determine the *nuclear magnetic moment* from the H.F.S. splitting, the vector model will be used and then the results will be corrected in the usual way. We have already mentioned that the energy displacement of a term, as a result of the interaction of the nuclear moment with an electron, is given by the scalar product of the nuclear

moment, $\boldsymbol{\mu}$, and the magnetic field, $\mathbf{H}$, which the electron produces at the position of the nucleus. The field is composed of two terms: $\mathbf{H} = \mathbf{H}_l + \mathbf{H}_s$.

$\mathbf{H}_l$ is the field produced by the spinless electron. From the Biot-Savart law, this is at every instant:

$$\mathbf{H}_l = \frac{1}{c}\frac{\mathbf{r} \times \mathbf{i}}{r^3}$$

where $\mathbf{i} = -e\mathbf{v}$ is the current strength transported by the electron, and $\mathbf{r}$ is the position of the electron viewed from the nucleus. As $m\mathbf{r} \times \mathbf{v} = \mathbf{d}$ is the angular momentum and this is quantized, $\mathbf{d} = \hbar\mathbf{l}$, this position of the magnetic field is:

$$\mathbf{H}_l = -\frac{e\hbar}{mc}\frac{1}{r^3}\mathbf{l}$$

$\mathbf{H}_s$ is the magnetic field produced by the spin of the electron at the position of the nucleus. Since the spin, $\frac{1}{2}\hbar\mathbf{s}$, is related to the magnetic dipole moment, $\boldsymbol{\mu}_e = (e\hbar\mathbf{s}/mc)$, $\mathbf{s}$ the field becomes:

$$\mathbf{H}_s = \operatorname{grad}\left(\frac{\mathbf{r}\,\boldsymbol{\mu}_e}{r^3}\right) = \frac{e\hbar}{mc}\left\{\frac{\mathbf{s}}{r^3} - 3\frac{(\mathbf{rs})\mathbf{r}}{r^5}\right\}$$

If in Equation (28) for the energy displacement we put the expressions for $\mathbf{H}_l$ and $\mathbf{H}_s$, we obtain:

$$\Delta E = \frac{e\hbar}{mc}\frac{1}{r^3}\boldsymbol{\mu}\left\{1 - \mathbf{s} + 3\frac{(\mathbf{rs})\mathbf{r}}{r^2}\right\}$$

In order to signify that the magnetic moment, μ, of the nucleus has the same direction as the nuclear spin, $\mathbf{i}$, we write: $\boldsymbol{\mu} = (\mu/i)\mathbf{i}$. We now apply a familiar consideration from the vector model theory of the Zeeman effect. The vector model states that the vector $\mathbf{i}$ is not free but that it precesses about the direction of $\mathbf{j}$. In a time average we must, therefore, consider, instead of $\mathbf{i}$, its component in the $\mathbf{j}$-direction. Because of their periodic change the time average of the other components vanishes:

$$\bar{\mathbf{i}} = \frac{(\mathbf{ij})\mathbf{j}}{j^2}$$

We have, therefore:

$$\Delta E = \frac{e\hbar}{mc}\frac{1}{r^3}\frac{(\mathbf{ij})}{j^2}\frac{\mu}{i}\mathbf{j}\left\{1 - \mathbf{s} + 3\frac{(\mathbf{rs})\mathbf{r}}{r^2}\right\}$$

To determine the scalar product of $\mathbf{j}$ with the bracketed expression, we first form $\mathbf{j} = \mathbf{l} + \mathbf{s}$, and then multiply term by term, obtaining:

$$\mathbf{l}^2 + 3\frac{(\mathbf{rs})(\mathbf{rl})}{r^2} - \mathbf{s}^2 + 3\frac{(\mathbf{rs})^2}{r^2}$$

The second summand vanishes. Since $\hbar\mathbf{l} = m(\mathbf{r} \times \mathbf{v})$ is perpendicular to the vector $\mathbf{r}$, $\mathbf{rl} = 0$. In the last term we must again average over the entire path of the electron. The vector, $\mathbf{s}$, can be taken as constant during this average, since it precesses much more slowly than the period of the electron. The last term becomes simply $= \mathbf{s}^2$ and cancels the preceding term. The remaining term gives:

$$\Delta E = \frac{e\hbar}{mc}\frac{1}{r^3}\frac{(\mathbf{ij})}{j^2}\frac{\mu}{i}l^2$$

Analogously to the derivation of Equation (29), we can evaluate the scalar product by means of the vector model. This is:

$$(\mathbf{ij}) = {}^1/_2(f^2 - j^2 - i^2)$$

This completes the classical calculation. The transition to the quantum mechanical picture is effected by first introducing the average value:

$$\overline{(1/r^3)} = \int dV\psi^*(1/r^3)\psi$$

in place of $1/r^3$, using the electron eigenfunction. Secondly, expressions of the form $j(j+1)$ are put in place of the squares of the angular momenta. The result is the formula for the energy displacement of a hyperfine structure term:

$$\Delta E = \frac{e\hbar}{2\,mc}\,\overline{(1/r^3)}\,\frac{\mu}{i}\,\frac{l(l+1)}{j(j+1)}\,[f(f+1) - j(j+1) - i(i+1)] \tag{31}$$

The factor, l, contained in the numerator of this formula might lead also to the supposition that S-terms do not split. This assumption is not correct, because for S-terms the average $\overline{(1/r^3)}$ becomes infinitely large, as we are dealing with "pendulum paths" for which the electron also reaches the point $r = 0$.

The average value $\overline{(1/r^3)}$ is very sensitive with regard to the choice of the correct eigenfunctions. For example, use of the approximately correct "hydrogen-like" eigenfunction in the case of ^{23}Na gives a magnetic moment of 22 nuclear magnetons, instead of the correct value of 2.1 nuclear magnetons. As the region of small r is highly favored in the average $\overline{(1/r^3)}$, the eigenfunction must be well known in the neighborhood of the nucleus. The strongest deviations between the Schrödinger and Dirac theories also occur in this immediate region, so that $\overline{(1/r^3)}$ must be calculated with the help of the Dirac theory in order to obtain usable results. This complicated method may be avoided by applying the following alternative: In ordinary fine structure, also, the quantity $\overline{(1/r^3)}$ enters. Therefore, this quantity need not be calculated but may be taken directly from the empirically known splitting of the fine structure. All these considerations have the character of approximations and, in general, especially in the heavy elements, they give no greater than $\pm 10\%$ accuracy for the nuclear magnetic moment.

16. Atomic Beam Method

Stern and Gerlach showed in 1921 that the magnetic moment of the atom can be measured if a beam of atoms is passed through a nonhomogeneous magnetic field. An atom with a magnetic moment, **M**, obtains an additional potential energy:

$$V = -(\mathbf{HM}) \tag{32}$$

and the deflecting force:

$$\mathbf{K} = \text{grad}\,(\mathbf{HM}) \tag{33}$$

acts on the atoms of the beam. If the magnetic field, **H**, is nonhomogeneous, this force is different from zero and gives rise to a measurable deflection of the beam.

Since 1931, Rabi and his students have tried to extend this method of the Stern-Gerlach experiment to the measurement of nuclear magnetic moments. The fundamental idea can easily be made clear if we consider as an example ^{23}Na. The atomic beam comes

from an "oven" of such low temperature that no spectral terms other than $^2S_{1/2}$ are excited. This is a great advantage of the atomic beam method over the spectroscopic. We do not observe transitions between terms which require calculation in order to determine the terms themselves, but only the ground term $^2S_{1/2}$, is present. If the magnetic field, **H**, is not too large, a splitting of the Na-beam into two components takes place, corresponding to the orientation of the moment of the electron envelop (which arises only from the electron spin), parallel or antiparallel to the field. If a photographic plate is brought behind the nonhomogeneous magnetic field, two lines will appear upon it. The magnetic moment of the electron cloud, in this case equal to a Bohr magneton, can be calculated from the distance between the lines.

The foregoing is nothing other than the normal Stern-Gerlach experiment. However, if we make the atomic beam very narrow, both lines exhibit a splitting into four components. Even a weak magnetic field is sufficient to uncouple nuclear spin and electron envelop. The nuclear spin, **i**, orientates itself with quantized components, m_i, with respect to the field. In our example, $i = {}^3/_2$, so that the possible values are $m_i = +{}^3/_2, +{}^1/_2, -{}^1/_2, -{}^3/_2$, and altogether four components appear. The nuclear spin can be determined from this number and the nuclear magnetic moment can be found from the magnitude of the splitting.

The ideal case described here is usually not realized experimentally or theoretically. Experimentally, it is hardly possible to observe splitting into such fine components without enormous intensity losses. Actually, one observes only a broadening of the original line. Theoretically, also, matters are more complicated and the uncoupling must be studied very carefully.

Coupling for an atom not in a magnetic field consists, first, of an addition of **l** and **s** to form **j** and, secondly, of an addition of **j** and **i** to form **f**. In a very weak magnetic field, this vector, **f**, will also orientate itself with respect to the field so that it has a quantized component in the field direction. This is the Zeeman effect of H.F.S. If the field is stronger, the coupling between **j** and **i** is lost. The quantum number, **f**, then becomes meaningless; the coupling of **i** to **H** and of **j** to **H** is then stronger than that of **i** and **j** to each other, and both vectors set themselves up independently with quantized components, m_j and m_i, with respect to the field. This is the other limiting case, the Paschen-Back effect of H.F.S., which we have already described for the ^{23}Na example.

Breit and Rabi calculated the splitting for the transition region between the two limiting cases for the term in which we are especially interested, $^2S_{1/2}$ ($j = {}^1/_2$, $l = 0$). Entering into this calculation as a characteristic parameter is the ratio of the coupling energy of **j** and **H** to that of **j** and **i**. This quantity is:

$$x = \frac{2\,\mu_0 H}{\Delta E} \tag{34}$$

where μ_0 is the Bohr magneton and ΔE is the H.F.S.-splitting of the term without the magnetic field, i.e., the distance of the components with $f = i + {}^1/_2$ and $f = i - {}^1/_2$. The two cases, $x \ll 1$ and $x \gg 1$, evidently correspond precisely to the Zeeman effect and the Paschen-Back effect of the H.F.S. The formula for the deflecting force which acts on the atomic beam may be obtained from Equation (33) and V:

$$\mathbf{K} = -\frac{dV}{dH}\,\mathrm{grad}\,H = f\,(x)\mu_0\,\mathrm{grad}\,H \tag{35}$$

where:

$$f(x) = \pm \frac{\dfrac{m}{i+\dfrac{1}{2}} + x}{\sqrt{1 + \dfrac{2mx}{i+\dfrac{1}{2}} + x^2}} \tag{36}$$

For the Zeeman effect $m \equiv m_f$ and for the Paschen-Back effect $m \equiv m_i + m_j$. So long as the deflections experienced by the beam remain small, certainly a fair approximation may be obtained by putting these deflections simply proportional to the deflecting force and, therefore, proportional to $f(x)$.

The accompanying table presents the relationships for nuclear spin $i = {}^3/_2$.

$i = {}^3/_2, j = {}^1/_2$						
m	Stat.* weight	Partial states in the Zeeman effect ($m = m_f$)	Partial states in the Paschen-Back effect ($m = m_i + m_j$)	$f(x)$	$f(0)$	$f(\infty)$
$+2$	1	$f = i + j$	$m_i = {}^3/_2, m_j = {}^1/_2$	$+1$	$+1$	$+1$
$+1$	2	$f = i + j, f = i - j$	$m_i = {}^1/_2, m_j = {}^1/_2$ and $m_i = {}^3/_2, m_j = -{}^1/_2$	$\pm\dfrac{x + {}^1/_2}{\sqrt{1 + x + x^2}}$	$\pm{}^1/_2$	± 1
0	2	$f = i + j, f = i - j$	$m_i = -{}^1/_2, m_j = {}^1/_2$ and $m_i = {}^1/_2, m_j = -{}^1/_2$	$\pm\dfrac{x}{\sqrt{1 + x^2}}$	0	± 1
-1	2	$f = i + j, f = i - j$	$m_i = -{}^3/_2, m_j = {}^1/_2$ and $m_i = -{}^1/_2, m_j = -{}^1/_2$	$\pm\dfrac{x - {}^1/_2}{\sqrt{1 - x + x^2}}$	$\pm{}^1/_2$	± 1
-2	1	$f = i + j$	$m_i = -{}^3/_2, m_j = -{}^1/_2$	-1	-1	-1

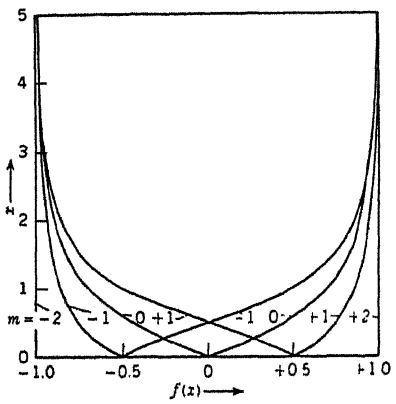


FIG. 13. The transition between Zeeman effect and Paschen-Back effect in the hyperfine structure of the ground term of sodium.

This quantity, $f(x)$, is plotted as a function of x in Figure 13. It gives the picture of the splitting directly. To be sure, a normalization is applied, the total width of the splitting independently of the field strength being set equal to 2. Actually, the absolute magnitude of the splitting, on account of the factor grad H in Equation (35), goes to zero for small x. With this representation of the splitting, the first two procedures for determining the nuclear spin and the nuclear magnetic moment can be made clear.

1. **Rabi's Method.** The figure is cut *horizontally*, i.e., the line diagram is measured for a given magnetic field, the nuclear spin, i, is obtained from the number of components, and x is calculated from the relative line distances, using Equation (36) or the table. The H.F.S.-splitting, ΔE, of the ${}^2S_{1/2}$ term for a given magnetic field may then be obtained from Equation (34). Using this result, we may calculate the magnetic moment by the procedure given on page 31.

2. **Cohen's Method.** The figure is cut *vertically* at the position $f(x) = 0$, i.e., the magnetic field and, hence, the quantity x is varied and the undeflected intensity is observed. The advantage of this null method is that the measured beam always has the same direction

in the magnetic field, so that exact knowledge of the field at every point is not necessary. Figure 13 shows that for $i = {}^3/_2$, maxima of undeflected intensity must exist at $x = 0$ and $x = {}^1/_2$. From a knowledge of the number and position of these points, i and the magnetic moment may be determined.

To obtain a clearer conception, we shall estimate the order of magnitude of the magnetic fields which are to be applied. First, let the parameter, x, in Equation (34) be of order of magnitude 1. Then we must have:

$$H \sim \frac{\Delta E}{2\mu_0}$$

According to Figure 12, the H.F.S.-splitting for the ^{23}Na ground state is 0.0583 cm^{-1} = $1.962 \cdot 10^{-16}$ erg and $\mu_0 = 0.922 \cdot 10^{-20}$ gauss cm^3; hence, we obtain $H = 620$ gauss. Fields of this order of magnitude may be set up without difficulty. The order of magnitude of the required field nonhomogeneity may be obtained by calculating the deflection, s, from the deflecting force, $\mathbf{K}$, or from the deflecting acceleration, $\mathbf{K}/M$. If a is the length of the nonhomogeneous field, the deflection in the field is:

$$s = \frac{1}{2}\frac{\mathbf{K}}{M}\left(\frac{a}{v}\right)^2 = \frac{\mathbf{K}a^2}{4E} \tag{37}$$

As $f(x)$ in Equation (35) is of order of magnitude 1, the order of magnitude of the force has the value $\mu_0 \cdot \text{grad } H$, or:

$$\text{grad } H \sim \frac{4\,Es}{\mu_0 a^2}$$

If we substitute for E the thermal energy at room temperature, ${}^3/_2\,kT$, and put $s = 0.1$ cm and $a = 20$ cm, we obtain $H \approx 7500$ gauss/cm. The chief experimental difficulty of the method lies in the production of such large nonhomogeneities. As H should be of order of magnitude 600 gauss, it must vary from 0 to 600 gauss over a distance of less than 1 mm in order to possess this nonhomogeneity. Apparently, also, field lengths of several decimeters are necessary in order that the required nonhomogeneity does not become larger. The use of slower beams, say the use of very cool ovens as sources, also acts in the same manner.

17. Sign Determination and Resonance Method

The dilemma of small intensities or bad resolution, existing in atomic beam methods just as in mass spectrography, was solved in 1936 by Rabi by the introduction of a focusing procedure. If, in Equation (37), we put μ grad H for the deflecting force, then μ stands for the component of the atomic magnetic moment in the direction of the field. In the transition region between the Zeeman and Paschen-Back effects, it naturally depends on H. The beam is thus deflected by a nonhomogeneous field 1 by:

$$s_1 = \frac{\mu_1\,\overline{\text{grad } H_1}\,a_1^2}{4E}$$

where the bar indicates a proper average over the field nonhomogeneity. If we produce behind this first field a second one with reversed direction of gradient, the beam will be deflected back by an amount:

$$s_2 = \frac{\mu_2 \overline{\text{grad } H_2}\, a_2^2}{4\,E}$$

Those beams for which $s_1 = s_2$ will be observed behind the second field as undeflected intensity, or:

$$\mu_1 \overline{\text{grad } H_1}\, a_1^2 = \mu_2 \overline{\text{grad } H_2}\, a_2^2 \tag{38}$$

This focusing condition is independent of the energy of the particles (velocity focusing).

This focusing procedure leads to two new methods. The first is a determination of the sign of the magnetic moment, and the second gives precision values of the magnetic moment by direct measurement, without recourse to the roundabout way of H.F.S.-splitting.

1. Sign Determination. Neither the H.F.S. method nor the atomic beam method, described on page 32, permits the determination of the sign of the nuclear moment from investigation of S-states, which always split into two components of equal intensity. Such

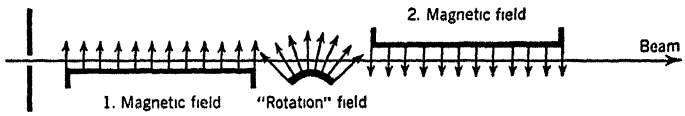


FIG. 14. Scheme of Rabi's beam method for determination of the sign of nuclear magnetic moments.

a determination, by methods hitherto described, is possible only for terms of higher angular momenta; there the interval rule is used and one observes whether a normal or a reversed multiplet is present. As the P-term splitting is much smaller than that of the S-term, a method which also makes possible sign determination from S-terms is worth seeking.

The device introduced by Rabi for this purpose consists in putting another magnetic field between the two nonhomogeneous magnetic fields. The force lines for this field are radial, as Figure 14 shows schematically. Viewed from an atom traveling from left to right, this field appears like a rotating field which rotates with a frequency ω_r, dependent upon the atomic velocity. As long as ω_r is small with respect to the Larmor frequency:

$$\omega_L = \frac{\mu H}{\hbar i} \tag{39}$$

with which the magnetic moment vector of the atom precesses about the field direction at a given instant, this rotation has no essential influence. If, however, ω_r increases so much that it is comparable to ω_L, such a rotating field can produce so-called *nonadiabatic transitions* to a noticeable degree. Here the atom keeps its total angular momentum and changes its component in the field direction (Umklapp processes).

As a simple example, consider an atom with $i = 1/2$ in ^2S-state with $j = 1/2$, say an H-atom. Again, as in the table on page 34, the function $f(x)$, which represents a measure of the deflection in the nonhomogeneous field, is given, and, in addition, the total angular momentum, f, and the magnetic quantum number, m (where an f-term signifies one that, with decreasing field, passes continuously into a term with angular momentum f). The assignment of the two middle lines depends on whether μ is positive or negative. As long as no rotating field is present, this difference is meaningless. All four quantum states have

the same statistical weight and have the same intensity in a splitting diagram. If the rotating field be introduced, a fixed but different portion of atoms splits apart from each of the four rays. This portion has a value μ_2 for the component of magnetic moment in the second nonhomogeneous field such that an originally present focusing no longer exists. These particles, therefore, are no longer counted in a detector placed behind the second nonhomogeneous field. These residual intensities are given in the accompanying table as a function of a parameter, α, which is dependent upon the form of the field and upon the atom velocity. The exact value of this parameter is unimportant. It is essential only that the residual intensities of the two middle lines turn out to be different, according as the nuclear magnetic moment is positive or negative: In the one case the second line, in the other case the third, remains undimmed.

Line	(x)	Nuclear moment positive				Nuclear moment negative			
		Term		Intensity		Term		Intensity	
		f	m	Without Rotational field	With Rotational field	f	m	Without Rotational field	With Rotational field
1	$+1$	1	-1	1	$\cos^4 \alpha$	1	-1	1	$\cos^4 \alpha$
2	$+x/\sqrt{1+x^2}$	0	0	1	1	1	0	1	$2 \sin^2 \alpha \cos^2 \alpha$
3	$-x/\sqrt{1+x^2}$	1	0	1	$2 \sin^2 \alpha \cos^2 \alpha$	0	0	1	1
4	-1	1	$+1$	1	$\sin^4 \alpha$	1	$+1$	1	$\sin^4 \alpha$

Experimentally, this method proceeds in the following manner: The second nonhomogeneous field is introduced, the rotating field is out, and the current strength in the first field is varied. In our example the focused intensity runs through two maxima, the first arising from the simultaneous focusing of lines 1 and 4, the second from lines 2 and 3. A "selector slit" is then placed before the second field. The simultaneously focused atoms of lines 2 and 3 are spatially separated at this point because the particles belonging to one line are first deflected downward and then upward whereas, on the contrary, those of the other line are first deflected upward and then downward. With the help of the selector slit, line 3, for example, can be suppressed, so that only the focused intensity of line 2 is obtained. Variation of the first magnetic field, with the second field held fixed, will now produce just one maximum. If, in our example, the rotating field is introduced, the intensity will remain undimmed for positive nuclear moment, that is, the maximum will pass through at its former peak. On the other hand, a weakening occurs for negative nuclear moment. This makes possible a differentiation between the two signs.

2. Resonance Method. The procedure described above can naturally be used also to determine the absolute value of the nuclear moment. The H.F.S.-splitting of the term can again be determined from the current strength necessary to give rise to the maximum. This method for determination of nuclear moment is also an indirect method. A slight change of the described procedure, which Rabi carried out in 1938, permits the direct measurement of the nuclear moment, μ—or, more accurately, of the so-called "nuclear g-factor," the ratio μ/i.

Instead of the rotating field, a homogeneous field, H, is applied, which is so strong that it gives rise to a complete decoupling of **i** and **j**, i.e., that it evokes the Paschen-Back effect of H.F.S. This field alone would not influence the course of the experiment, as the particles experience no deflecting force in a homogeneous field. A weak oscillating field is, however, superposed at right angles to it. This, like the preceding rotational field, is in the position

to give rise to the characteristic intensity dimmings of the individual lines by means of non-adiabatic transitions from one Paschen-Back component to another. This dimming is small, because the strength of the oscillating field is small compared to that of the homogeneous field, H; it possesses, however, a sharp resonance, if the oscillation frequency, ω, coincides with the Larmor frequency, $\omega_L = \mu H/\hbar i$, in the homogeneous field, H. μ is not the moment of the entire atom, but that of the nucleus alone, which in the Paschen-Back effect precesses entirely independently of the electron envelop. Now, varying H for fixed oscillation frequency, ω, we can directly determine:

$$\mu = \hbar i\omega/H_{\text{res}} \tag{40}$$

by measurement of that field strength, $H = H_{\text{res}}$, for which maximum dimming takes place. These resonance positions are very sharp, so that this method is suitable for precision measurements of nuclear magnetic moments. These measurements have been carried out in many cases. The results so obtained are by far the best which could be produced until now. Nuclear moments determined by this method can be given with an uncertainty of only a few per thousand. A special advantage is that as a result of the decoupling of nuclear spin and electron cloud, the method is suitable for application to molecular beams instead of atomic beams.

G. The Quadrupole Moment

18. Determination of Quadrupole Moment from H.F.S.

We saw, on page 29, that the H.F.S.-lines for terms of higher angular momenta must obey an interval rule, which is due to the fact that the interaction energy between the nuclear magnetic moment and the angular momentum of the electron term is proportional to $\mu \cos(\mathbf{i}, \mathbf{j})$. Deviations from this rule can occasionally occur, arising, on the one hand, from opposing energetic perturbations of closely neighboring electron terms and, on the other hand, from relativistic correction terms in heavy atoms. These additional terms are proportional to $\mu^2 \cos^2(\mathbf{i}, \mathbf{j})$.

The H.F.S. photographs of europium show rather large deviations of this type, which Schüler and Schmidt tried to explain in 1935. This element consists of two isotopes of masses 151 and 153. The magnetic moment of ^{151}Eu is about 2.2 times as great as that of ^{153}Eu, so that the H.F.S.-splitting of the light isotope is considerably greater than that of the heavy one. In both these isotopes, Schüler and Schmidt found the presence of an additional term which is proportional to $\cos^2(\mathbf{i}, \mathbf{j})$. However, this additional term was not proportional to μ^2. For then the effect for ^{151}Eu would have to be 5 times as large as for ^{153}Eu, but actually its effect was at the most so large, and tended rather to be somewhat smaller. This is, accordingly, a case in which the deviations from the interval rule may be said with certainty to be not explicable in either of the two manners previously discussed.

From their observations Schüler and Schmidt concluded that this deviation was to be attributed to a new property of the atomic nucleus, namely, an electrical quadrupole moment which was smaller for ^{151}Eu than it was for ^{153}Eu. In fact, it may be shown that such a quadrupole moment must lead to a H.F.S. which is proportional to $\cos^2(\mathbf{i}, \mathbf{j})$.

The concept of quadrupole moment stems from classical potential theory. Let us assume that the nucleus possesses a charge distribution arising from the protons. This

distribution is not exactly spherically symmetric but is rotationally symmetric about the axis singled out by the nuclear spin. The potential field in the neighborhood of such a charge cloud can always be represented by a power development in ordinary (Legendre) spherical harmonics:

$$V(r, \theta) = \frac{e}{r}\left[Z + \frac{\alpha}{r}P_1(\cos\theta) + \frac{1}{2}\frac{q}{r^2}P_2(\cos\theta) + \ldots\right]$$

where θ is the angle with respect to the nuclear spin axis and r is the distance from the center of the nucleus. The first term in this development corresponds to the point charge and is the ordinary Coulomb field. The second term would correspond to an electric dipole moment, $e\alpha$. Experience shows that such an electric dipole moment does not manifest itself for atomic nuclei, nor is it conceivable because the nuclear constituents are protons and neutrons (no negative components). The next term in the development is the first term to measure the deviation from spherical symmetry. The factor, q, is called quadrupole moment.

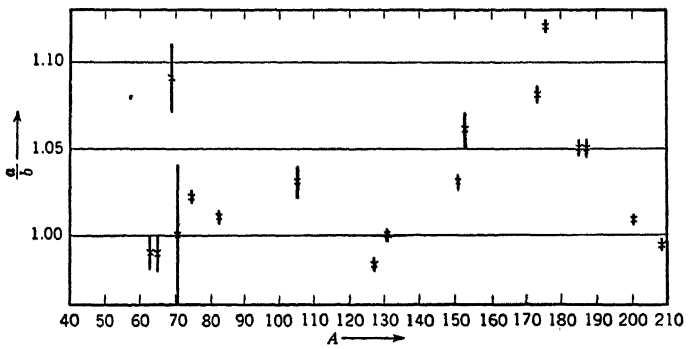


FIG. 15. Ratio of nuclear axes when viewed as ellipsoidal, as calculated from the quadrupole moment. The arrows correspond to the limits of experimental error. A systematic dependence on mass number, A, appears to be indicated, but is uncertain because of the large scattering and the small number of experimental points.

This quantity, q, has a very simple intuitive meaning. If we conceive of the nucleus as an ellipsoid of rotation, the semiaxis of which in the direction of the rotation axis is of length a, and the semiaxis at right angles is of length b, we have:

$$q = \frac{2}{5}Z(a^2 - b^2) \tag{41}$$

Thus, the quadrupole moment measures directly the magnitude of the flattening or length ening of the ellipsoid. If q is negative, the nucleus is flattened; if q is positive, the nucleus is elongated.

The measurements carried out until now on an entire series of nuclei are grouped in Table I. The greatest deviations from spherical symmetry lie in the region of the rare earths and in the heavier nuclei. The axis ratio, a/b, calculated according to Equation (41), is plotted in Figure 15. It is seen that most of the nuclei investigated possess an elongated and not a flattened form. This should be interpreted as an experimental indication that the atomic nucleus should not be thought of as a "liquid drop," but in many respects is rather to be compared with a rigid body.

II. NUCLEAR REACTIONS

19. Methods of Observation

The detection and investigation of nuclear reactions are always connected with the observation of the fragments and secondary products appearing in these processes, particularly their type, number, energy, and angular distribution. Charged particles (α-particles, protons, recoil nuclei, disintegration products) and neutrons occur as fragments. If the reaction gives rise to a radioactive nucleus, then positive or negative electrons occur as secondary disintegration products. Furthermore, in many cases, γ-radiation connected with the reaction can be observed. The methods of detection are different, depending upon the product to be observed.

1. Observation of Charged Heavy Particles. The first observations of any nuclear reactions were achieved by means of the scintillation method, which, through decades, played an important role in natural radioactivity. This method makes use of the property of certain substances (like phosphorus and ZnS) to produce a small flash of light at a point hit by α-particles or similar fragments of several MeV energy. The observation of these flashes or scintillations, though indeed possible, was entirely abandoned more than ten years ago as the procedure was exceedingly troublesome and, because of its subjective character, unreliable. Today, it is only of historic interest.

The methods used nowadays to detect charged particles, as well as to determine their energies, are based almost entirely upon their ionizing power. A charged particle of sufficiently high energy (i.e., more than several keV), in passing through a gas, produces ion pairs, one ion pair for approximately every 30 eV, to a large degree independently of the nature of the gas. Or, in other words: *A charged particle gradually loses its kinetic energy by continuous ionization along its path, and it loses about 30 eV per ion pair produced.* The two most important methods of detection are the ionization chamber and the cloud chamber.

(*a*) *Ionization Chamber.* If the particle to be detected travels inside a condenser, the positive ions will be separated from the electrons by the contained field strength, and will be drawn to the condenser plates. The current flowing from one of the condenser plates may then be measured. If in addition to detecting the particles one wants also to measure their energy, as is usually the case, three elements have to be heeded: First, the substance from which the particles originate should be a thin layer, so that the released particles are not noticeably slowed down by the material. This limits the amount of substance which may be used to produce the reaction. For another reason, however, thicker layers are often used nevertheless: If particles of only a certain energy are produced in a reaction and if thick layers are used, all energies up to this particular one are observed; from the upper limit observed in a continuous spectrum, conclusions may be drawn with

regard to the original energy. Secondly, the chamber dimensions should be at least as large as the full range of the particles, otherwise the particles will collide with the walls before they are entirely stopped, and fewer ion pairs will be produced than the number corresponding to their energy. Accordingly, either the chamber should be large enough or, if for some reason this is not possible, it should be filled with gas at high pressure (several atmospheres) in order to shorten the range of the particles. The simplest way to ascertain whether this condition is fulfilled is by experiment: Increase the pressure in the chamber and observe whether the measured (apparent) energy of the particles still increases with the pressure or whether it is independent of the pressure (saturation). Thirdly, no noticeable recombination probability must exist for the ion pairs formed. This circumstance is avoided either by low pressure or, if this is not possible without violating the second qualification, by a strong electric field which quickly separates the ions and attracts them to the condenser plates. For ordinary chamber dimensions of several centimeters and for atmospheric pressure, a potential of a few hundred V is chosen; and for higher pressures, correspondingly higher potentials up to several thousand V are chosen. The lifetime of the ions is approximately 10^{-4} sec.

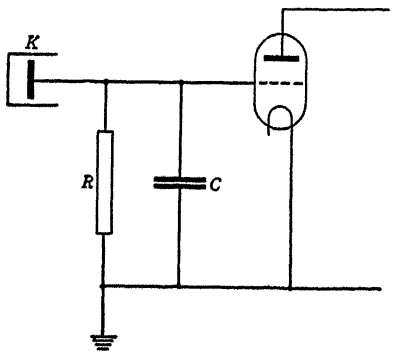


FIG. 16. Scheme for coupling an ionization chamber, K, to the first tube of the amplifier.

If we want to detect a particle of, say, 3 MeV in the ionization chamber, an electric quantity of 10^5 ions or electrons, conveyed in 10^{-4} sec, has to be measured, i.e., of $Q = 1.6 \cdot 10^{-14}$ coulomb. Hence, a current, $i = 1.6 \cdot 10^{-10}$ amp, flows from the condenser plate during this short time interval. It is clear that such a weak and short current pulse cannot be measured quantitatively with any accuracy. Therefore, the ionization chamber has to be connected to an *amplifying device*. Figure 16 shows a common coupling scheme. The current is applied to the grid of the first tube where it produces a small increase, δV_g, in the grid voltage, V_g. The leak resistance, R, is necessary so that the electric charge can flow off again after a particle has been registered. Thus, the grid is not charged continuously and is reset for the next particle. If the resistance is too large, the grid will take too long to be ready again; if too small, then too large a part of i will immediately leak off through R without charging the grid. Hence, the order of magnitude of R is fixed: it should be such that the time necessary to discharge the grid capacity is similarly of the order of magnitude 10^{-4} sec. The capacity of the grid is increased by inserting the condenser, C. Its order of magnitude is determined by two conditions: on the one hand, compared to the self-capacity of the conducting elements, which is not well defined and not constant, C should be large; on the other hand, it should be as small as possible, because the strength of the voltage pulse, $\delta V_g = Q/C$ produced by the charge, Q, varies inversely with C. Therefore, C is best chosen approximately $\approx$ 10 cm $\approx 10^{-11}$ F. The voltage pulse will then be somewhat weaker than $1.6 \cdot 10^{-14}$ coulomb/10^{-11} F $= 1.6 \cdot 10^{-3}$ V; it will actually be somewhat weaker because not all of the charge reaches the condenser, part of it leaking off directly through R to the earth. In any case, pulses of the order of 10^{-3} V may be expected on the grid of the first tube. The leak resistance is obtained from the fact that the discharge of the condenser is proportional to $e^{-t/RC}$. The time constant, RC, should be 10^{-4} sec; this is the case for $R = 10^7\Omega$.

A change in grid voltage of the first tube causes a change in plate current according to the definition:

$$S = \left(\frac{\partial i_A}{\partial V_g}\right)_{V_A}$$

for the mutual conductance, S, of the tube characteristic. The plate circuit of the first tube is coupled in a suitable way to the grid of the second tube. The second grid is then subject to considerably larger voltage pulses. This process is continued through several stages until the pulses are sufficiently magnified. It is important that all amplifiers work in the linear part of their characteristic to assure amplification of large and small pulses by the same factor. The strength of the current pulse in the plate circuit of the last tube is proportional to the energy of the particle to be registered, which then becomes accessible to direct measurement. An amplifier that satisfies this condition is called a *linear amplifier*.

Pulses may be registered in different ways. For example, an oscillograph may be inserted in the last plate circuit so that the pulses appear directly as deflections on the oscillograph and are registered on a passing strip of film by the light beam. Then it is necessary only to calibrate the sizes of the deflections in terms of an energy scale by means of a standard source which produces particles of known energy. The energy of the individual particles is then determined by measuring directly the length of the individual deflections.

In order to register a great number of particles, the pulses of the last tube may very conveniently be applied to the grid of a *thyratron*. A thyratron is a gas-filled tube and has, therefore, a well-defined firing potential. If this is, e.g., 50 V, and all pulses of more than 30 V in the last plate circuit are to be registered, a starting voltage of 20 V has to be initially applied to the thyratron so that the necessary 50 V will just be reached, or will be exceeded, by the pulses to be investigated. Moreover, a suitable relay system has to be inserted, causing the thyratron to be extinguished shortly after firing, thereby resetting it for the next particle. The current in the thyratron circuit then flows to a mechanical counter. In this way, with a given thyratron voltage, one measures the number of particles which appear in the ionization chamber within the measuring time interval and which possess an energy greater than a certain given energy. This method is, of course, also particularly well suited for the investigation of continuous energy spectra.

The method permits the registration of as many as approximately 1,000 particles a minute. For greater numbers of particles, the resolving power of the counters no longer suffices, nor can the thyratron be extinguished rapidly enough. In this instance, so-called *scale counters* are built with several thyratrons in parallel, one of which is always ready while all the others are still in use. As the counter is inserted in the circuit of only one of these thyratrons, only that particle will be counted which obtains response in this particular thyratron, so that with n thyratrons exactly every nth particle will be registered. An arrangement for great numbers of particles which is very popular in America is the "scale of eight" counter, which responds only to every eighth particle.

(*b*) *Cloud Chamber*. If a gas saturated with any vapor is adiabatically expanded by sudden increase in volume, the partial saturation pressure falls below the real vapor pressure due to the lowering of temperature in this process. Supersaturation results, causing part of the vapor to precipitate in the form of droplets. Apart from the walls of the chamber, the centers of such condensation are all condensation nuclei, i.e., ions which are present

in the gas-filled space. We are thereby in possession of a device that can make individual ions visible by causing a visible droplet to condense about each ion.

The use of such a device to make fast rays visible goes back to C. T. R. Wilson. First of all, care must be taken that the chamber is entirely free from stray ions. This is done by applying an electric field of a few hundred v. This field is then removed and the expansion is started immediately afterwards. If ionizing particles enter during the expansion, i.e., after the field has been removed, then the ions produced by them are not drawn away immediately, but remain several tenths of a second at the place of their formation and thus make visible the path of the particle as a cloud track. This time interval is sufficient to obtain a picture of the track in a photograph (or two stereographic photographs). The tracks later become diffused, partly because of turbulent flows in the gas which can never be quite suppressed, partly because of diffusion, i.e., Brownian movement. By expanding quickly before, and slowly after, the main expansion, the useful time interval can be extended to several seconds ("slow" cloud chamber), but by then the tracks are generally fairly indistinct.

The very nature of this apparatus does not permit any precision measurements. Still, it gives valuable information if a preliminary view of new nuclear reactions is primarily desired. The cloud chamber usually provides a clearer and more physical picture of the processes than the ionization chamber. On the other hand, direct measurements of the energy of the particles are difficult to procure in the cloud chamber, but, instead, their range, i.e., the length of the cloud track, is obtained. Therefore, knowledge of the range–energy relation is generally necessary in order to measure the energy. Furthermore, the cloud chamber affords a determination of the ionization density, i.e., the number of ions produced per cm of path. Due to the difference in ionization density, different types of particles may often be easily distinguished at a glance.

(*c*) *Measurement of Energy by Electromagnetic Action.* Although the ionizing effect of particles is needed for their detection, other procedures may be employed for the determination of their energy. Apart from the determination of energy from their range, mentioned in the preceding paragraph, use is made of the analogy which exists between these fast, charged particles and ordinary "canal rays." The attempt has been made to apply to these nuclear fragments the methods of electric and magnetic deflection of rays. The main difference between this method and the technique of canal rays, such as in mass spectrography, is due to the much higher energy of particles usually found in nuclear fragments. Here the rays are much more difficult to deflect and, therefore, require stronger fields in order to obtain measurable deflections.

The idea of bending the cloud track into a circular arc by applying a homogeneous magnetic field succeeded only with field strengths of the order of magnitude of 20,000 gauss. Not until 1938, when Joliot succeeded with the aid of the strong Paris magnet, was it possible to obtain a measurable deflection in the cloud chamber.

Another procedure suggested by mass-spectrographic technique is electric deflection. In the last few years, Allison and his collaborators have tried to measure the energy of particularly slow particles, i.e., particles of only a few hundred keV, by singling out one ray and passing it through an electric radial field. In this manner a few precision measurements could be carried out in the region of smaller energies, which is otherwise rather inaccessible.

2. Observation of Neutrons. As the neutron itself does not possess any power of

ionization, the methods discussed so far are not practicable in this case. Neutrons can be detected only by means of their interaction with atomic nuclei. Another peculiarity appears here: not only fast, but also extremely slow neutrons, with an energy of only a fraction of an eV instead of several million eV, may interact with atomic nuclei.

If fast neutrons enter an ionization chamber filled with hydrogen, the hydrogen nuclei will scatter some of the neutrons. In this process a scattered neutron loses, on the average, half of its energy to the scattering proton, which now can be detected by its ability to ionize. In a similar way, one may work with ionization chambers filled with helium. The result is, of course, always a continuous spectrum of the energies of protons or helium nuclei, the upper limit of which corresponds to the neutron energy. The procedure can, therefore, be applied fairly easily if the problem is to detect neutrons of a homogeneous energy group. As soon, however, as many such groups or even a whole continuum of neutron energies appear, this method requires a rather troublesome numerical evaluation into which the dependence of the scattering cross section on the energy also enters. This quantity is not too well known, particularly not for helium. Therefore, energy measurements of neutrons are almost always subject to much greater uncertainty than measurements of charged particles.

Conditions improve if the recoil protons are observed not in an ionization chamber but in a cloud chamber. As the directions of the particles participating in the collision can also be obtained from the cloud track, the law of conservation of momentum as well as of conservation of energy may be used in the evaluation, and for every single recoil particle observed it is possible to determine the energy of the corresponding impinging neutron. This advantage contrasts with the disadvantage that only moderate accuracy can be obtained in measuring the angles at the tracks, which are always of finite width. The cloud chamber plainly does not allow precision measurements under any circumstances.

If only the matter of counting the number of neutrons and not of measuring their energy is involved, it is sufficient to make any suitable substance radioactive under the influence of neutrons, using the strength of the activation as a measure of the number of neutrons that fall on the substance. Expediency in this case requires slowing down the neutrons first to very small energies, of the order of magnitude of 1 eV or less. This is done simply by letting them pass through a substance containing hydrogen. We have already seen that, on the average, neutrons lose half their energy per collision in elastic collisions with the equally heavy protons, so that their energy after twenty collisions is reduced to the fraction $2^{-20} = 10^{-6}$ of their initial energy. As their mean free path between collisions is about 1 cm in water and paraffin, a layer of 5 to 8 cm is sufficient to slow them down to that extent (see page 53). The activation of a suitable indicator substance, such as Rh-foil or Dy_2O_3 placed behind the water or paraffin, is measured. Instead, a *boron-chamber*, that is, an ionization chamber the walls of which are lined with a thin layer of boron or which is filled with BF_3-gas, may be placed behind the paraffin. As slow neutrons having a large effective cross section release α-particles out of boron, this process is fairly sensitive as well. The α-particles ionize and can be registered in the usual way by a linear amplifier.

The slowing down of neutrons also indicates the way to obtain shielding from neutrons. This protection is particularly necessary near the American cyclotron plants with their immense radiation intensity. All neutrons are first slowed down by a thick water layer, so that most of them enter into thermal equilibrium with the surrounding water. Their

energies are then only of the order of $^1/_{30}$ eV. Boron, which absorbs slow neutrons very strongly, is dissolved in the water. The few neutrons which are still able to leave the water can be entirely absorbed in a thin Cd-sheet, so long as their energies are smaller than about 0.2 eV.

3. Observation of Electrons. Electrons may accompany nuclear reactions as secondary electrons of γ-radiation. Mostly, however, they appear only as a subsequent phenomenon in connection with the formation of a radioactive substance in a nuclear reaction, and continue to be emitted after minutes, hours, or years. As they are charged particles, ionizing along their path, all methods of detection for charged particles can, in principle, be applied to them. However, the slowing down of electrons takes place much more gradually than that of heavy particles. They produce fewer ion pairs per cm of their path, and hence possess much longer paths. Therefore, observations can hardly be made with an ionization chamber or a linear amplifier. In the cloud chamber their tracks usually run across the whole chamber; they can easily be distinguished from those of the heavy particles by their much lower ionization density.

The *Geiger-Müller counter* replaces the ionization chamber as the most convenient instrument for the detection of electrons. A thin wire is stretched along the axis of a thin metal cylinder with a wall-thickness of about 20 to 100 μ Al—thin enough to allow fast electrons to enter. A rather high electric potential is applied between cylinder and wire (more than 1000 V), making the cylinder negative with respect to the wire. The field strength inside is then radially directed, and greatest near the wire. If we denote the radius of the wire by r_0, the radius of the cylinder by r_a, and the applied voltage by V, the field strength becomes:

$$E_r = \frac{V}{\ln r_a/r_0} \frac{1}{r}$$

At $r = r_0$, for usual dimensions of, say, $r_0 = 0.1$ mm and $r_a = 1$ cm, and for a voltage $V = 1000$ V, the field strength becomes 22,000 V/cm.

Such a strong electric field lies approximately at the limit of spontaneous electric discharge. If an electron that is to be registered comes from a radioactive source and passes through the counter, then the electrons produced by ionization along its path are accelerated by the field towards the wire to such an extent that they possess enough energy to ionize in their turn the ions of the enclosed gas with which they collide. This means that they produce new electrons and an electron avalanche is formed, so that the current pulse flowing between cylinder and wire during the gas discharge becomes much stronger than it would be if only the few electrons produced directly by the primary particles were the carriers of the discharge (*multiplication effect*). This pulse is applied to the grid of an amplifier tube, just as in the arrangement of an ionization chamber. Although the number of secondary electrons produced in the counter by the primary electron is much smaller than the number produced by a heavy particle in an ionization chamber, the multiplication effect achieves a comparable effect on the grid.

If the current forming in the counter leaks directly away to the earth, a spontaneous discharge takes place, i.e., a continuous current as a consequence of the single impulse. In order to avoid this discharge, i.e., in order to stop the current immediately after the electron has been registered, a high resistance is inserted in the circuit. In this way it is assured that the current can never exceed a certain value, $i_0 = V/R$. It is known from the theory

of electrical discharge in gases that a certain minimum current is necessary to keep up a spontaneous discharge. If i_0 is fixed below this minimum by a sufficiently high resistance, the current obviously cannot become permanent. On the other hand, to prevent the period for the redischarge of the grid or of the condenser coupled with the grid from becoming too large, the leak resistance, R, must not be too great. The order of magnitude of the leak resistance is determined by these two requirements.

The current in the counter apparently depends to a great extent not only on the nature and amount of the enclosed gas, but also on the couplings connecting the counter to the earth and to the grid of the first tube. By suitably choosing the available quantities, a rather wide potential range may be obtained, within which the number of current pulses given off by the counter is exactly proportional to the number of primary electrons which pass through the counter, independently of the voltage applied. The reason for such a wide counting range is the artificial widening of the range of induced discharge.

The counter registers every particle entering through its wall, regardless of its energy. The simplest way to determine the electron energies seems to be to insert absorbing foils (say of aluminum) between source and counter. The relation between absorption coefficient and energy has to be known in order to make the determination. This method is very suitable for obtaining an estimate of the penetrating power of the electron observed, but does not allow any exact measurements.

Better procedures are based on the property of small magnetic field strengths, of a few hundred to a thousand gauss, to deflect electrons of a few MeV to a considerable extent. As homogeneous fields of this order of magnitude can be produced without great effort in spaces of several decimeters, the deflection of electrons in the cloud chamber can thus be observed directly. In a field, H, an electron of velocity, v, experiences the Lorentz force $(e/c)vH$ perpendicular to its path. The radius of curvature, ρ, of the circular orbit thus produced is obtained by putting the Lorentz force equal to the centrifugal force, mv^2/ρ. This results in the equation:

$$mv = \frac{e}{c} H\rho \tag{42}$$

The product of radius of curvature and field strength is, therefore, proportional to the momentum of the electron. The law remains valid in this form even in the case of relativistic velocities, i.e., if the momentum no longer equals mv. The following relation then holds:

$$E + mc^2 = \sqrt{(pc)^2 + (mc^2)^2} \tag{43}$$

by means of which the energy, E, can be computed from the momentum, that is, from $H\rho$. In this definition, E does not contain the rest energy.

This type of cloud chamber measurements does not give a high degree of precision. The path of an electron outside of a magnetic field is usually not a perfectly straight line like that of heavy particles, but is slightly bent by multiple scattering. The determination of the energy from the radius of curvature consequently becomes increasingly unreliable if the electron energy decreases and if the gas pressure in the cloud chamber rises.

The neatest method for determining electron energies again uses magnetic deflection, but now the particles travel through a vacuum in order to avoid scattering. This is the basis for the *magnetic β-spectrograph*, in which use is made of the property that a beam of

electron rays deflected through 180° in passing through a magnetic field is brought to a focus, similar to Dempster's mass spectrograph. The arrangement is exactly the same as in Figure 3 (page 5), except that the source is put in the position of the first slit for the canal rays, and a thin-walled counter for the emerging electrons is placed behind the last slit. In this way even precision measurements are possible. One source of error is, of course, due to the fact that electrons emerging from deeper layers of the source lose part of their energy in passing through the upper layers. In order to avoid this loss, it is important to work with thin layers.

4. Observation of γ-Rays. Hard electromagnetic radiation (γ-radiation) with a quantum energy, $h\nu$, say between 0.1 MeV and 20 MeV, is observed by means of secondary electrons produced by this radiation. The γ-radiation ionizes by photoelectric effect. The energy of electrons ejected from the K-, L-, M-shell of the atoms by a light quantum, $h\nu$, is, therefore, $h\nu - E_K$, $h\nu - E_L$, $h\nu - E_M$. These energies will be observed as spectral lines in the magnetic β-spectrograph in the presence of a γ-line. The energy of the γ-quantum itself must be determined from its spectrum, and this is not always easy.

In order to detect the presence of γ-radiation directly, its high penetrating power can be utilized. Although a few mm of aluminum are sufficient to absorb fast electrons and still thinner layers are sufficient to absorb α-particles, a thickness of 1 cm or more is necessary to absorb γ-rays to a noticeable extent. Usually lead, which is much more absorbing, is used as an absorbing medium instead of aluminum, but, even then, plates of several cm thickness are needed.

Three reasons may be cited for the absorption of γ-rays: They produce secondary electrons by a photoelectric process, to an increasing extent as $h\nu$ becomes small. In lead, this is the preponderant cause of absorption for energies below 1 MeV. Furthermore, they are scattered by the electrons of the atoms; the scattering cross section also decreases slowly with increasing energy. The radiation would, therefore, become more and more penetrating with increasing energy, were it not for the possibility of a new process taking place above $h\nu = 2\,mc^2 \approx 1$ MeV (m = electron mass) - the conversion of a photon into a positron and an electron when traversing the strong electric field in the neighborhood of an atomic nucleus (pair creation). Clearly, this process cannot occur unless at least twice the rest energy of the electron is available. Beyond this limit its probability increases fairly rapidly with $h\nu$. The absorption coefficient, μ, as a function of the quantum energy has, therefore, a pronounced minimum; radiation of a few MeV is more penetrating than is harder, as well as softer, radiation. The three effects together give the following (computed) values for the absorption coefficient in lead:

$h\nu = 0.7$	1.0	1.5	2.0	3	4	5	7	10	MeV	
$\mu = 1.14$	0.77	0.56	0.50	0.45	0.46	0.48	0.53	0.61	cm^{-1}	Pb

An arrangement which is often used to detect γ-rays is the *coincidence counter*. The radiation is directed through two counters placed some distance behind each other. In the wall of each counter the γ-radiation releases secondary electrons, especially if the walls are constructed of lead 1 mm thick, instead of thin Al-foil. The counters are connected in such a way as to record coincidences, i.e., the counting device registers a particle only if, within the resolving time, both counters simultaneously send a pulse to the grid of their tubes. This coincidence is most easily effected by connecting the tubes of the last stage of both counter amplifiers in parallel and applying to them a grid bias (positive) such that a

continuous current flows in them. If one counter responds, the current in the corresponding tube of the last stage is interrupted, but can still flow through the other tube. The output current will be interrupted, and the counting device will respond only if the current in both tubes of the last stage is cut off simultaneously. In this way, essentially only those coincidences which are caused by a γ-ray are counted. The absorption of γ-rays in layers of lead, which may be inserted between the two counters, can be immediately determined from the reduced frequency of coincidences. The tabulated absorption coefficients for different energies show, however, that this method is hardly practicable for the determination of energies in the range from 1.5 to 10 MeV.

20. Sources of Radiation

In order to induce nuclear reactions, projectiles are needed to bombard the nuclei which are to be transmuted. Constituents of the atomic nuclei themselves are preferred for this purpose, i.e., protons, neutrons, deuterons, α-particles. In addition, γ-rays used for this purpose play a particular role. Whereas nuclear particles can directly dislodge particles out of the nucleus, it is possible by means of γ-rays to excite nuclei, and if the energy of the radiation is sufficiently high, even to produce a nuclear photoelectric effect in which a neutron leaves the nucleus. In this case, the quantum energy of the γ-rays has to be higher than the energy binding a neutron to the nucleus. As the neutron-binding energy is usually about 8 MeV according to the mass defects, a γ-energy of more than 8 MeV is generally required.

1. Charged Particles. A fundamental difference exists between charged projectiles (protons, deuterons, α-particles) and uncharged ones (neutrons), with respect to the required projectile energy of nuclear constituents. Whereas neutrons, even if they are very slow, react with atomic nuclei, a considerable energy is required for the positively charged projectiles to overcome the Coulomb repulsion and thus bring together the two participants in the reaction. As they have to approach each other as closely as 10^{-12} cm or less, an energy of a few MeV is required even for atomic nuclei with small charge number, increasing up to about 50 MeV for the heaviest nuclei.

The usual procedure for obtaining particles of such high velocity is to produce a canal ray of the desired type of particles and to accelerate the ray by passing it through an electric field. In order to increase the energy of the canal ray particles up to 1 MeV, they must obviously pass a potential difference of 1 MV. Hence, *high voltage apparatus* is necessary for the acceleration. Cockcroft and Walton, in 1932, were the first to combine canal rays and acceleration in a high-voltage unit. High voltages were produced by using Greinacher's "cascade generator," which was also used successfully by later investigators. Since then, other methods of high-voltage production also have come into use. The transformer circuits which were developed in x-ray technique are usually not applicable for the purposes of nuclear physics because they produce alternating voltage. Van de Graaff's arrangement can be constructed with relatively modest means and is very much used; it is an adaptation of the induction machine to a technical scale. A large collecting sphere is continuously charged by means of a moving belt. The charge is sprayed onto the belt, then passes into the inside of the sphere and is imparted to the brushes connected to the sphere.

The same problem is solved in an entirely different way in the *cyclotron*, invented by

Lawrence and Livingston. The particle, instead of passing through a wide potential range, is accelerated several times in succession by the same smaller potential drop. This acceleration is attained by bending the particles into circular paths in a magnetic field, so that each particle has to enter the same electric field again and again. Figure 17 shows this principle diagrammatically. A pressure of the same magnitude as that in a canal-ray tube exists in the flat chamber shown in the figure. An ion source is placed approximately in its center. Two iron plates form the walls of the chamber and also serve as the pole pieces of a powerful electromagnet. Thus, a strong homogeneous magnetic field crosses the chamber perpendicular to the plane of the paper. If the ions have a small velocity component perpendicular to the plane of the paper at the time of their production, they move along a circular path within the plane of the paper. Another chamber, insulated against the first one, is built inside and cut in two along a diameter. The ions move within these two semicircular chambers, usually called "dees" because of their shape. The two dees serve as electrodes to which a high-frequency voltage is applied.

Assume that an ion leaves the electrode D_1, traveling left to right in the plane of the paper, at the moment when the electric potential has its positive maximum. The ion is then accelerated to the right, passes through the slit between D_1 and D_2, and continues its motion in D_2 on a circular orbit with a somewhat larger radius. The frequency of the electric field is adjusted so that the field is reversed and reaches its negative maximum potential when the ion leaves D_2. The ion receives another accelerating impulse, enters D_1 with increased speed, and moves on a circular orbit with a still greater radius. This interplay of repeated accelerations in the gap can be continued more and more, because the time required to pass through an electrode is the same for fast and for slow particles, so that the acceleration which can be achieved is limited practically only by the size of the electrodes. The fastest particles travel very near the periphery of the chamber. They can be removed by an electrostatic field deflecting through a slit at E; thus, a beam of particles of high energy is obtained which may be used for experiments in nuclear physics.

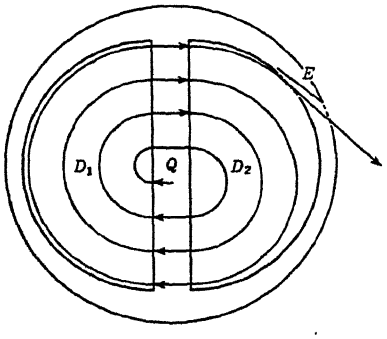


FIG. 17. Principle of the cyclotron.

The relation between radius of path, ρ, velocity, v, and magnetic field strength, H, can be ascertained from Equation (42), where m is now the mass of the ion and e its charge. The time required to pass one dee is:

$$T = \frac{\pi\rho}{v} = \frac{\pi mc}{eH}$$

and is evidently independent of the speed of the ions. The frequency of the alternating electric field has to be adjusted so that a change of poles takes place precisely in this time interval, i.e.:

$$\nu = \frac{eH}{2\pi mc} \tag{44}$$

The maximum energy of the emerging ions is obtained by replacing ρ by the radius, r, of the dee:

$$v_{\max} = \frac{eHr}{mc} \qquad \text{or} \qquad E = \frac{m}{2} v_{\max}^2 = \frac{e^2(Hr)^2}{2\,mc^2} \tag{45}$$

If the magnetic field is given, the required frequency, ν, of the alternating field can thus be calculated from Equation (44), and the energy which can be attained with a particular radius, r, can be obtained from Equation (45). As the maximum energy is proportional to the quantity e^2/m, which is the same for protons and α-particles ($1^2/1$ and $2^2/4$, respectively), protons and α-particles receive the same energy in the same cyclotron, whereas deuterons ($e^2/m = 1^2/2$) receive only half as much. The frequency required for the control is proportional to e/m, according to Equation (44), and hence is the same for deuterons and α-particles, whereas it is twice as high for protons. The values for α-particles, if the radius $r = 30$ cm, are:

H	Frequency, ν	Wavelength $\lambda = c/\nu$	Energy, E
3,000 gauss	$2.29 \cdot 10^6$ sec^{-1}	131 m	0.39 MeV
9,000 gauss	$6.87 \cdot 10^6$ sec^{-1}	43.6 m	3.52 MeV
15,000 gauss	$11.5 \cdot 10^6$ sec^{-1}	26.2 m	9.76 MeV

For technical reasons, the frequency, ν, is usually kept constant and the magnetic field, H, is varied so as to fulfill the resonance condition represented by Equation (44). Instead of Equation (45), the following expression is then obtained:

$$E = 2\pi^2 m \nu^2 r^2$$

so that the particle energy furnished by a cyclotron is proportional to the mass. A cyclotron furnishing α-particles of 12 MeV yields only 6 MeV deuterons and 3 MeV protons.

Technically, two requirements have to be fulfilled in the construction of a cyclotron. First, a field of about 10,000 gauss has to be produced in a space half a meter long and, second, a high-frequency emitter of considerable power with a wavelength of less than 100 m is necessary. The power is determined by the fact that the two dees have to be charged in the short time, T, their capacities being given by the arrangement. A normal radio transmitter of about 20 kW power is needed, and an equivalent amount of power has to be additionally supplied to operate the magnet. For this reason the construction and operation of a cyclotron are highly expensive.

Due to the frequency condition of Equation (44), the cyclotron can also be considered as a mass spectrograph: At a certain frequency a beam of particles is obtained corresponding to a certain value of e/m. Alvarez and Cornog took advantage of this fact in order to detect the presence of a very rare ^{3}He isotope in natural He by means of helium-filled dees. They estimated its relative abundance from the current intensity and used it as a projectile for nuclear transmutations. In principle this can be done with all elements, but so far the possibilities thus revealed have not been utilized in any way.

The technical possibilities described above have been available for only about eight years. Before that, the only available sources of radiation were the naturally produced α-particles emitted by some radioactive substances. This was a great limitation. First, no way existed to vary the nature of the projectiles, so that one was confined to only certain types of nuclear reactions. Secondly, such sources of radiation were considerably weaker than those available today. For the cost of 1 g Ra, a high-voltage apparatus may be constructed which will give the same α-yields as may be derived from 1 kg Ra.

From the foregoing discussions, the following rule generally holds: If high intensities are desired, but not extremely high energies (potential range 1 to 3 MeV), a canal-ray tube followed by acceleration in a high-voltage apparatus is recommended. The current intensi-

ties thus obtained range from 100 to 1000 μamp. If, however, very high particle energies are desired (3 to 30 MeV), one is confined to the cyclotron, although it produces much weaker intensities (0.1 to 10 μamp).

2. Neutrons. The production of neutrons is possible, in principle only, by means of nuclear reactions, where the neutrons appear as fragments. First, therefore, suitable nuclear reactions have to be induced by means of charged particles. A neutron intensity is then obtained which, by a considerable factor, is smaller than the intensity of the source of the charged particles. This factor is called the yield of the reaction. The yield is, at best, around 10^{-4}, but is usually considerably lower.

Neutron sources differ, therefore, according to the different ways in which charged particles are produced. At first, neutrons could be produced only in reactions which were induced by the α-rays of naturally radioactive substances, such as radium or radon. Here the reaction ${}^{9}_{4}\mathrm{Be}\ (\alpha, n)\ {}^{12}_{6}\mathrm{C}$ is customarily used. A radium salt is mixed thoroughly with beryllium powder, or else radium emanation is separated from radium and led into a small tube containing beryllium. The amount of emanation in equilibrium with 1 mg radium yields $1.1 \cdot 10^{8}$ α-particles per sec (together with its disintegration products), but yields only about 20,000 neutrons per sec in the beryllium tube. The yield is, therefore, $2 \cdot 10^{4}/1.1 \cdot 10^{8} = 2 \cdot 10^{-4}$. The disadvantage of using emanation lies in the short half-life period of radon (3.8 days). Using radium itself means confining this valuable element entirely to neutron production. One has to decide between these two possibilities from case to case, depending upon which disadvantage is more important.

If high-voltage apparatus is available, the fairly high yield from reactions of the type (d, n), induced by bombardment of light elements with deuterons, can be utilized. If the deuteron energies are low, the reaction ${}^{2}_{1}\mathrm{D}\ (d, n)\ {}^{3}_{2}\mathrm{He}$ has an especially high yield. If, however, deuteron energies of more than 400 keV are available, the use of the reaction ${}^{7}_{3}\mathrm{Li}\ (d, n)\ {}^{8}_{4}\mathrm{Be}$ is more favorable. The yield of ${}^{9}_{4}\mathrm{Be}\ (d, n)\ {}^{10}_{5}\mathrm{B}$ is then greater than that of ${}^{2}_{1}\mathrm{D}\ (d, n)\ {}^{3}_{2}\mathrm{He}$, but less than that of the lithium reaction. The yield of this last reaction, at a deuteron energy of 400 keV, is about $4 \cdot 10^{6}$ neutrons per sec for every μamp of deuteron current hitting the lithium target. At 600 keV it is $21 \cdot 10^{6}$ and at 800 keV it is as high as $106 \cdot 10^{6}$ neutrons per sec. Two reasons may be cited for this rapid rise: With greater energy of the projectile, the particles enter deeper into the bombarded layer and also approach closer to the nuclei to be transmuted (penetrating the Coulomb field more easily).

These numbers show immediately the immense superiority of the high-voltage apparatus compared to natural α-emitter neutron sources. With 600 keV, the (Li + D) reaction yields per μamp about as many neutrons as 1 g Ra mixed with Be. Even small high-voltage apparatus produce current intensities of about 20 to 50 μamp, hence neutron intensities equaling the yield of as many grams of radium are not difficult to obtain.

For special purposes it is often important to have available sources which yield neutrons of a particular energy. In this regard, the (D + D) reaction, in which neutrons of a uniform energy of slightly more than 2.5 MeV (or somewhat more, according to the deuteron energy) are emitted, is especially important. The reactions Li + D and Be + D furnish a very complicated energy spectrum reaching to 13.4 MeV and 3.9 MeV, respectively, in the case of small deuteron energies. The same is true for the reaction Be + α, which also yields high-speed neutrons. If fairly low-energy neutrons are desired, the reaction ${}^{12}_{6}\mathrm{C}\ (d, n)\ {}^{13}_{7}\mathrm{N}$ may be used, although a noticeable yield starts only at 800 keV and remains small throughout; it produces only neutrons of several hundred keV. These are

like the so-called photoneutrons, which are knocked out of beryllium by the γ-radiation of RaC (2.22 MeV γ-energy) and have an energy of about 700 keV. They may be produced by enclosing the RaC-source in a small tube and surrounding it with a greater amount of Be-powder. Due to this separation, only the γ-radiation can act on the beryllium, whereas the α-particles do not reach it.

The production of slow neutrons plays an important role in neutron physics. If neutrons produced by any of the sources mentioned above pass through a thick layer of water, paraffin, or any other hydrogenous material, they are slowed down by elastic collisions with the hydrogen nuclei. As they have the same mass as protons, they transfer in each such collision, on the average, half of their energy to a proton. After 20 collisions their energy is, therefore, reduced, on the average, to a fraction 2^{-20} or 10^{-6} of their initial energy. This slowing-down mechanism operates only until the energy of the neutrons reaches the order of magnitude of the thermal energy of protons, i.e., about $^1/_{30}$ eV at room temperature. However, the slowing-down process is further impeded in the region of about 1 eV by the binding of protons to the molecular structure; thus, the transfer of momentum during the impact is disturbed.

The free path between collisions in water or paraffin is of the order of $\lambda = 1$ cm. If, after a collision, all directions are equally probable, the neutron traverses the distance $\sqrt{N}\lambda$ in air after N collisions. λ is still somewhat greater than 1 cm for the first collisions, and the scattering in the forward direction is strongly preferred. Hence, layers about 8 cm thick are needed to slow down the majority of the neutrons, with initial energy of several MeV, to thermal energies. An energy distribution is obtained which agrees fairly well with the Maxwell distribution in the thermal region, but decreases much more slowly as it approaches high energies. Whereas in the Maxwell distribution law the number of neutrons with energies between E and $E + dE$ falls off as $e^{-E/kT}$ for large E, the decrease here is proportional only to $E^{-3/2}$. Hence, a considerable number of neutrons is still available with energies between 1 eV and 100 eV.

For many experiments it is desirable to separate this somewhat higher energy region from the thermal region. The easiest way to effect the separation is to insert a cadmium sheet less than 1 mm thick. Cadmium has the property of absorbing thermal neutrons almost entirely, but is almost transparent to neutrons of energies higher than about 0.4 eV.

3. γ-Rays. Originally, the term γ-radiation was limited only to the very hard wave radiation of at least 100 keV energy emitted from certain radioactive substances. Later investigation has shown that such rays of very much smaller energies can be detected, down to less than a few keV, i.e., in a frequency range usually included in the x-ray band. Modern high-voltage technique, on the other hand, has made possible the production of extremely hard x-rays, with energies as high as approximately 1 MeV.

The hardest γ-lines of precisely this type are usually needed to produce nuclear transformations. Because it is difficult to produce them as x-rays, the use of natural sources has maintained itself against the competition of high-voltage apparatus, markedly more than in the case of corpuscular rays. Apart from the γ-line of 2.22 MeV of RaC mentioned previously in connection with photoneutrons, the radiation of ThC″ (2.62 MeV), the hardest ray emitted from natural sources, is of particular importance in nuclear physics. Its energy is sufficient to drive a neutron out of the ^{9}Be-nucleus and to decompose the deuteron into its two constituents.

For the large majority of nuclei, a transmutation by γ-rays can be expected only

above a quantum energy of about 8 MeV. Natural sources, as well as x-ray methods, fail here. This region has been made accessible by Bothe and Gentner, who made use of the formation in certain nuclear reactions of a very hard γ-radiation. If a proton is captured by a $^7_3$Li-nucleus, a γ-radiation of not less than 17 MeV energy is produced. Substances can thus be exposed to this hard radiation by placing them immediately behind the lithium layer which is bombarded by protons. This arrangement led Bothe and Gentner to the discovery of the reaction (γ, n)—the nuclear photoelectric effect—in numerous elements.

21. Range–Energy Relation

An α-particle of an energy of a few MeV travels a distance of several cm, in air. Protons and deuterons of the same energy travel even farther. However, the intensity of a particle beam emitted from a source does not under any circumstances decrease gradually, e.g., exponentially with increasing distance from the source, but all particles travel approximately the same distance. A sharply defined *range* exists, which increases with increasing energy of the particles. If the relation between range and energy is known, the measurement of the range, which is easily carried out, can be utilized immediately for the determination of the energy. For this reason the precise knowledge of the relation between energy and range is important for the evaluation of experiments in nuclear physics.

The first theory of the phenomena was developed by Bohr in 1913, and he based it on the following conception: The particles are slowed down, when they are flying past the atoms, by exciting the shell electrons—which Bohr at that time assumed to be quasi-elastically bound—to forced vibrations which used up part of the particle energy.

We shall outline the mathematical treatment of the process based on this classical representation. If m is the mass of the bound electron of charge e, and ω its proper frequency in the atom, the equation for the forced vibration is given by:

$$m(\ddot{\mathbf{r}} + \omega^2\mathbf{r}) = \mathbf{K}(t)$$

where $\mathbf{K}$ is the Coulomb force exerted on the electron by the passing particle of charge e' and mass M. If the path of the particle is known, $\mathbf{K}$ is known also as a function of time, and we obtain the solution:

$$\mathbf{r} = \frac{1}{m\omega}\int_{-\infty}^{t} \sin \omega(t - t')\mathbf{K}(t')dt'$$

This solution means intuitively that the continuous action of the force may be conceived simply as made up of short single impulses. An impulse at the time t', that lasts through the time interval dt' and has the intensity $\mathbf{K}(t')$, excites an oscillation with an amplitude proportional to $\mathbf{K}(t')dt'$, a frequency ω, and a phase that must be fixed in such a way that at the time of the impulse, i.e., for $t = t'$, the oscillation has a node. The solution of the equation of oscillation is the superposition of the action of all such impulses, and hence is given in the form of the foregoing integral. The appearance of the factor $1/(m\omega)$ in front of the integral is easily verified by insertion in the differential equation.

We want to give only a rough estimate of orders of magnitude. We may neglect the curvature of the path, i.e., we may assume that the particle passes the electron at distance p without being deflected. This is undeniably a fair approximation because the rectilinearity, for example of the tracks in the cloud chamber, shows that large individual deflections

are very rare, and hence do not noticeably influence the slowing-down process. If the particle travels with the velocity v, we can say, roughly: The Coulomb force acts during the time interval $\tau = 2\,p/v$ with the force $K = ee'/p^2$ at right angles to the path of the particle. The sine under the integral being of order of magnitude 1, the amplitude of the electron in this direction is, therefore, approximately given by:

$$x \approx \frac{1}{m\omega}\cdot\frac{ee'}{p^2}\cdot\frac{2\,p}{v}$$

the average mean velocity of the oscillating electron by:

$$\dot{x} \approx \omega x = \frac{2\,ee'}{mvp}$$

and the kinetic energy of the oscillation by:

$$E_{\text{kin}} = \frac{m}{2}\,\dot{x}^2 = \frac{2\,e^2e'^2}{mv^2p^2}$$

The kinetic energy is obtained by the electron at the expense of the particle, so that it must equal the loss of energy, Q, of the particle when the particle passes the electron at the distance p.

When the particle passes through the stopping substance, the energy lost to numerous atoms along the path length, Δs, has to be added. Assume the number of atoms in 1 cm^3 to be N; the number of electrons in 1 cm^3 is then NZ. If we put cylindrical zones, i.e., zones of equal p, around the path of the particle, the number of atoms contained in one such zone along the path interval, Δs, is $2\pi p\,dp\,\Delta s NZ$. The total energy lost along the interval Δs is then given by:

$$\frac{\Delta E}{\Delta s} = -\int Q 2\pi p\,dp\,NZ = -\frac{4\,\pi e^2e'^2}{mv^2}\,NZ\int\frac{dp}{p}$$

It is readily seen from the integral that the expression must not be integrated from zero to ∞. Indeed, physical arguments can be given to show that a minimum as well as a maximum p exists.

The smaller p is, the stronger the electron is excited, hence the larger the energy transferred to it. A particle of mass M, however, can never transfer the whole of its energy $Mv^2/2$ to an electron of mass m, if the law of conservation of momentum is to hold. The most energy that can be given up is:

$$Q_{\max} = \frac{2\,mv^2}{\left(1+\dfrac{m}{M}\right)^2} \approx 2\,mv^2$$

This energy is transferred according to our formula for E_{kin}, if p takes the value:

$$p_{\min} = \frac{\sqrt{2}\,ee'}{\sqrt{mv^2Q_{\max}}}$$

For larger p the electron is less excited, and the energy transferred becomes smaller. Quantum theory gives a lower limit for Q (and in this respect our reasoning differs from Bohr's original presentation). The electron has to be raised at least to the next excitation

level in order to take up any energy at all. If I is the average excitation energy of the atom, then:

$$Q_{\min} = I$$

and the corresponding distance:

$$p_{\max} = \frac{\sqrt{2}\, ee'}{\sqrt{mv^2 Q_{\min}}}$$

The energy loss is then given by:

$$\frac{\Delta E}{\Delta s} = -\frac{4\pi e^2 e'^2}{mv^2} NZ \ln \frac{p_{\max}}{p_{\min}} = -\frac{2\pi e^2 e'^2}{mv^2} NZ \ln \frac{2\, mv^2}{I}$$

Since the average excitation energy, I, appears only under the logarithm, the precise way of forming the mean value is of minor importance.

Our very rough method of computing may, of course, be wrong by numerical factors. The precise quantum–mechanical computation of the problem leads actually to an energy loss which is twice as large:

$$\frac{dE}{ds} = -\frac{4\pi e^2 e'^2}{mv^2} NZ \ln \frac{2\, mv^2}{I} \tag{46}$$

The velocities are then given by the stopping formula:

$$\frac{dv}{ds} = -\frac{4\pi e^2 e'^2}{Mmv^3} NZ \ln \frac{2\, mv^2}{I}$$

From this formula we can compute the range, s, i.e., the distance that a particle travels until it is slowed down from the initial velocity, v_0, to zero. We have only to integrate:

$$s = \frac{Mm}{4\pi e^2 e'^2 NZ} \int_0^{v_0} \frac{v^3 dv}{\ln \frac{2\, mv^2}{I}}$$

This expression has the form:

$$s = \frac{M}{e'^2} f(v_0) \tag{47}$$

and we obtain the two following statements:

1. α-particles and protons of the same velocity have the same range because their M/e'^2 is the same. Or: An α-particle of energy $4\,E$ has the same range as a proton of energy E.

2. A deuteron has twice as large a range as a proton of the same velocity, because M/e'^2 is twice as large for a deuteron as it is for a proton. Or: A deuteron of energy $2\,E$ has twice as large a range as a proton of energy E.

The integration over the velocity cannot be carried out in an elementary way; it leads to an integral logarithm. If, however, $2\, mv_0^2/I \gg 1$, we have the approximate formula:

$$s = \frac{Mm}{4\pi e^2 e'^2 NZ} \frac{v_0^4}{4 \ln \frac{2\, mv_0^2}{I}} \tag{48}$$

The range will, therefore, increase somewhat faster than the third, and somewhat slower than the fourth power of the velocity. This is in agreement with the empirical relation $s \propto v_0^3$, which was found a long time ago by Geiger for α-particles of an energy between 4 and 9 MeV. In the accompanying table, the range is tabulated as a function of energy for the most important types of particles in the energy region of practical interest. For protons and α-particles the empirical values have been used, as the conclusions drawn from Equation (47) do not very well apply to small energies. The ranges of deuteron and triton have been obtained by making use of those of the proton, and the ranges of ^{3}He by using those of α-particles. For heavier nuclei, a mean has been given of the values calculated with the help of proton and α-particle. These latter values are, therefore, rather inexact, especially for small energies.

Energy MeV	Range in cm air at 15° C and 760 mm Hg for								
	$^1_1$H	$^2_1$H	$^3_1$H	$^3_2$He	$^4_2$He	$^6_3$Li	$^7_3$Li	$^9_4$Be	$^{10}_5$B
2	7.06	4.6	3.8	1.10	1.05	0.42	0.41	0.24	0.14
4	23.1	14.1	10.8	2.88	2.49	0.90	0.87	0.47	0.30
6	46.3	28.1	21.2	5.51	4.61	1.56	1.50	0.77	0.48
8	77.3	46.2	34.5	8.81	7.35	2.48	2.28	1.14	0.70
10	115	68.0	50.2	12.44	10.55	3.55	3.24	1.59	0.96

It is easily seen that the existence of a sharply defined range also follows from our stopping formula. As about the same energy, approximately 30 eV, is required for each ion pair produced, the energy loss, dE, over the length, ds, is proportional to the number of ions formed in this distance and dE/ds is thus a direct measure of the ionization density along the path. The ionization density, however, increases towards the end of the path. If, as an approximation, Geiger's relation, $s \propto v^3 \propto E^{3/2}$, is used, then $dE/ds \propto s^{1/3}$, in which s is now the residual range, i.e., the distance from the end of the range. Evidently the ionization density increases towards the end of the range (Bragg). As the thickness of the track in a cloud chamber depends upon the ionization density, it follows that towards the end of the range the track becomes heavier and then breaks off suddenly.

The foregoing considerations, of course, no longer hold for the very last part of the range, i.e., if $Q_{max} = 2\,mv^2$ becomes smaller than $Q_{min} = I$. The particle is then no longer able to ionize. On the contrary, it will begin to capture electrons and to build up its own shell (Umladung phenomena). In this way its own charge will decrease and the process of stopping will be still more impeded. As this limit is not very sharply defined, the range is determined only up to the order of 1 mm air. If one puts $I = 30\,eV$, the condition $2\,mv^2 = I$ furnishes the following energy quantities: 14 keV for protons, and for a particle of mass M-times as great, an energy of M times 14 keV, i.e., approximately 50 keV for α-particles. But our theory fails at only four or five times this value. As an (empirical) range of about 2 mm air corresponds to an α-energy of 200 keV, all computed values are uncertain by amounts of this order. The differences of the values given in the accompanying table are, however, considerably more accurate because the uncertainty in the last part of the path disappears when differences are formed.

22. Conservation of Energy and Momentum in Nuclear Reactions

We will restrict ourselves to the usual type of nuclear reactions in which a projectile of mass m and velocity v hits a nucleus of mass M at rest, and a light particle of mass m'

and velocity v' and a heavy particle (recoil nucleus) of mass M' and velocity V' are formed. These two particles will move in directions making the angles φ and Φ, respectively, with the direction of motion of the incident particle.

We expect that the law of conservation of momentum is satisfied in such a nuclear reaction, i.e., the momentum of the projectile, $p = mv$, must equal the momenta of both fragments, $P' = M'V'$ and $p' = m'v'$. The law of conservation of momentum thus takes the form:

$$p = P' \cos \Phi + p' \cos \varphi$$
$$0 = P' \sin \Phi - p' \sin \varphi$$

All quantities occurring in these two equations can, in principle, be determined experimentally. The momentum, p, of the projectile follows from its energy, which depends upon the nature of the source of the projectile. The momenta of the two fragments can also be obtained from their energies in the ionization chamber. But it is not possible to determine the angles, which permit a direct determination of the correctness of the two equations. Observation in the cloud chamber is best suited for this purpose; here the momenta are obtained from the ranges (page 56), i.e., from the length of the tracks. Their directions give the angles φ and Φ by direct measurements.

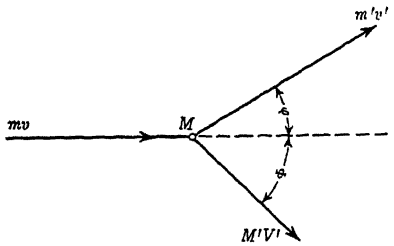


FIG. 18. Notations for a nuclear reaction.

Usually the track of the recoil nucleus, which obtains only a small part of the total momentum, is so short that a measurement of Φ is too inaccurate. Therefore, Φ is eliminated from the equations and only the relation:

$$P'^2 = p^2 + p'^2 - 2\,pp' \cos \varphi$$

thus obtained, is verified.

More detailed results are obtained by including the law of conservation of energy, which states that the sum of rest and kinetic energies of the participating particles is the same before and after the reaction. Denoting the kinetic energy of the projectile by $\epsilon = p^2/2\,m$ and the energies of the fragments by $\epsilon' = p'^2/2\,M'$ and $E' = P'^2/2\,M'$, we obtain:

$$(m + M)\,c^2 + \epsilon = (m' + M')c^2 + \epsilon' + E'$$

or:

$$\epsilon = \epsilon' + E' - (m + M - m' - M')c^2$$

The quantity:

$$Q = (m + M - m' - M')c^2 \tag{49}$$

is different from zero. Q is usually of the order of a few MeV due to the difference in the mass defects of the individual nuclei (the masses do not have exactly integer values). This quantity, Q, called *heat of reaction* or *reaction energy*,* analogously to chemical reactions, may be positive or negative. In the first case the reaction is *exothermic*, in the second *endothermic*.

Because it is difficult to obtain reliable experimental data regarding the recoil nucleus,

* In German: "Wärmetönung" or "Energietönung."

owing to its small range, the law of conservation of energy is used to eliminate P' and E' as well as Φ from the equations. Then:

$$Q = \frac{m' + M'}{M'}\epsilon' - \frac{M' - m}{M'}\epsilon - 2\frac{\sqrt{mm'}}{M'}\sqrt{\epsilon\epsilon'}\cos\varphi \tag{50}$$

By means of this equation the reaction energy, Q, can always be computed from the observed data, φ and ϵ', without knowledge of the mass defects, because without appreciable error we can substitute in Equation (50) the corresponding integer "mass numbers" (see page 8). Unless the observations are made in the cloud chamber, a particular angle is selected by suitable apertures so that only those fragments are observed which leave the bombarded substance, the "target," through this angle. Usually, one of the following arrangements is used:

$$\left.\begin{array}{ll} 1. \text{ Principal position, } \varphi = 0^\circ: & Q = \dfrac{m' + M'}{M'}\epsilon' - \dfrac{M' - m'}{M'}\epsilon - 2\dfrac{\sqrt{mm'}}{M'}\sqrt{\epsilon\epsilon'} \\ 2. \text{ Principal position, } \varphi = 90^\circ: & Q = \dfrac{m' + M'}{M'}\epsilon' - \dfrac{M' - m}{M'}\epsilon \end{array}\right\} \tag{51}$$

If one knows the reaction energy and is interested in the energy, ϵ', of the fragments, Equation (50) has to be solved only for ϵ'. One then obtains:

$$\sqrt{\epsilon'} = \frac{\sqrt{mm'}}{M' + m'}\sqrt{\epsilon}\cos\varphi + \sqrt{\left[\frac{M' - m}{M' + m} + \frac{mm'}{(M' + m')^2}\cos^2\varphi\right]\epsilon + \frac{M'}{M' + m'}Q} \tag{52}$$

In particular, for the second principal position, the simpler equation:

$$\epsilon' = \frac{(M' - m)\epsilon + M'Q}{M' + m'} \tag{53}$$

is obtained.

Two examples may serve to illustrate the formulas. For the exothermic reaction:

$$^2_1\mathrm{D} + {}^2_1\mathrm{D} \rightarrow {}^3_2\mathrm{He} + {}^1_0n$$

the reaction energy is given by $Q = 3.2$ MeV. The mass numbers are $M = 2$, $m = 2$, $M' = 3$, $m' = 1$. Hence, it follows from Equation (52):

$$\sqrt{\epsilon'} = \frac{\sqrt{2}}{4}\sqrt{\epsilon}\cos\varphi + \sqrt{\left(\frac{1}{4} + \frac{1}{8}\cos^2\varphi\right)\epsilon + \frac{3}{4}Q}$$

The yields of this reaction are fairly good even with small deuteron energies; for this reason, it has been studied very thoroughly for energies of only a few hundred keV. If we insert an energy value in this range, e.g., $\epsilon = 0.2$ MeV, the result for ϵ' (in MeV) follows:

$$\sqrt{\epsilon'} = 0.158\cos\varphi + \sqrt{2.45 + 0.025\cos^2\varphi}$$

It is seen that the variation with the angle depends mainly on the term before the square root. In particular, for $\varphi = 0^\circ$ $\epsilon' = 3.00$ MeV, for $\varphi = 90^\circ$ $\epsilon' = 2.45$ MeV, and for $\varphi = 180^\circ$ $\epsilon' = 2.00$ MeV. Depending on the direction, the energy of the emitted neutrons is 2 to 3 MeV, and this reaction can be used as a source of uniform neutrons with energies which can vary to a certain extent (see page 52).

An increase in the mass of the nucleus to be transmuted means a decrease in the momentum of the recoil nucleus; hence, the direction dependence also decreases. For the exothermic reaction:

$$^{27}_{13}\mathrm{Al} + {}^4_2\mathrm{He} \rightarrow {}^{30}_{14}\mathrm{Si} + {}^1_1\mathrm{H}$$

with $Q = 2.34$ MeV, $M = 27$, $m = 4$, $M' = 30$ and $m' = 1$, we have:

$$\sqrt{\epsilon'} = 0.0645\sqrt{\epsilon}\cos\varphi + \sqrt{2.26 + (0.838 + 0.004\cos^2\varphi)\epsilon}$$

In this case higher projectile energies are needed to produce the transmutation. For $\epsilon = 8$ MeV, the numerical values are $\epsilon' = 10.1$ MeV for $\varphi = 0°$ and $\epsilon' = 8.96$ MeV for $\varphi = 90°$.

If, on the other hand, the reaction energy, Q, is determined from the energy of the particles emitted in a certain direction, using Equation (50), the expression $m + M - m' - M'$ is known from Equation (49). *As three of the masses participating in a nuclear reaction are known, a determination of the reaction energy, Q, is equivalent to the new determination of a fourth mass. This method of determining the masses of nuclei accurately represents an important supplement of the mass-spectrographic method.* The extensive material obtained in this way is included in the appended tables.

So far we have restricted ourselves essentially to exothermic reactions. For endothermic reactions the same formulas hold, of course, except that $Q = -U$ is then negative. Such reactions require a certain minimum projectile energy, a threshold energy, ϵ_S, in order to occur at all. This is expressed mathematically by the fact that the radicand in Equation (52) becomes negative for $Q = -U$ if ϵ is too small. This gives for the threshold energy:

$$\epsilon_S = U\frac{M'}{M' - m + \dfrac{mm'}{M' + m'}\cos^2\varphi} \tag{54}$$

Consider an example: Haxby, Shoupp, Stephens, and Wells recently showed that the reaction:

$${}^{9}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{9}_{5}\mathrm{B} + {}^{1}_{0}n$$

takes place only if the protons have an energy of at least $\epsilon_S = 2.01$ MeV. For $M = M' = 9$ and $m = m' = 1$, Equation (54) has the form:

$$U = \frac{8}{9}\left(1 + \frac{1}{80}\cos^2\varphi\right)\epsilon_S$$

The angular dependence is very small. For the first principal position, $\varphi = 0°$, the reaction energy, $Q = -U$, is computed from the measured value of ϵ_S as -1.81 MeV.

23. The Neutron

The methods for determining the mass, spin, and magnetic moment of the proton, dealt with in Chapter II, cannot be applied without change to the other constituent of the nucleus, the neutron. As free neutrons do not occur in nature, but can only be produced artificially as disintegration products of nuclear reactions, the story of their discovery and the determination of their main properties is intimately connected with certain nuclear reactions which will now be discussed.

The discovery of neutrons is connected with the work of Bothe and Becker on the radiation emitted by a beryllium layer when bombarded with α-rays from polonium. Absorption coefficients of about (0.15 ± 0.05) cm^{-1} were measured in lead. As very little was known at that time about the absorbability of hard γ-rays, no more could be stated than that the radiation was more penetrating by a large factor than the hardest γ-radiation then known, i.e., 2.62 MeV. As the absorption coefficients (see page 48) are well known today and can readily be computed, we can state more precisely that the radiation is far

more penetrating than the most powerful γ-radiation. Therefore, the radiation observed by Bothe and Becker could not be wave radiation. Since a corpuscular radiation consisting of charged particles is still less penetrating, the only alternative is to assume *uncharged particles.*

Soon afterwards, Curie and Joliot found that the number of registered particles was doubled when a layer of paraffin or water was inserted between the Be-layer and the ionization chamber which was used for the measurements. They interpreted the phenomenon by assuming that protons were ejected from the layer and entered the chamber as strongly ionizing secondary radiation. They were still in the dark regarding the nature of the primary radiation. However, they deduced that a γ-radiation which was able to produce such fast recoil particles (protons of a few MeV) by a kind of Compton effect should have a quantum energy of at least 50 MeV. As the source of such a high energy was not readily perceptible, this experiment also indicated a particle radiation.

Chadwick continued these experiments and observed that other recoil nuclei, as well as protons, could be released by the radiation. He measured the energy of such particles by investigating the range of protons in thin aluminum foils, and that of nitrogen in the cloud chamber. In this way proton velocities were shown to extend up to $v_H = 3.3 \cdot 10^9$ cm/sec, and the velocities of the nitrogen nuclei up to $v_N = 0.47 \cdot 10^9$ cm/sec. As the masses of these particles are 1 and 14, the maximum velocity, v_n, of the inducing particles and their mass, M_n, can be obtained from the following equations, according to the laws of conservation of momentum and energy:

$$v_H = \frac{2\,M_n}{M_n + 1}\,v_n \quad \text{and} \quad v_N = \frac{2\,M_n}{M_n + 14}\,v_n$$

From the given rough numerical values, it follows that $v_n \approx v_H$ and $M_n \approx 1.16$.

To summarize: Be is bombarded by α-particles, and uncharged particles are emitted with a mass approximately equal to that of the proton. These particles were called neutrons by Chadwick. The following nuclear reaction takes place:

$$^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}n$$

It may be mentioned for the sake of completeness that later experiments by Rasetti disclosed that a γ-radiation is present as well. This can easily be verified today from the fact that the observed velocity, v_n, of the neutron does not correspond to the reaction energy resulting from the masses of the participants in the reaction.

If neutrons are uncharged, their absorption in material layers must be due to their interaction with atomic nuclei, for example by elastic collisions in which they are slowed down by transferring part of their energy to the nucleus struck, or else by nuclear transmutations induced by the neutrons. These processes are directly known to us today, and they suffice to explain the observed absorption, taking into consideration that part of the Be-radiation consists of γ-quanta.

It can be shown by determining the number of ion pairs produced by the neutron per cm of path that the absorption does not take place due to stopping by ionization, the neutron having a very much smaller charge than that of the proton. Such measurements were carried out by Dee in the cloud chamber by counting the cloud droplets; he found that, at most, 1 ion pair per 1 m path was produced by the Be-neutrons. As these neutrons have an energy of about 5.7 MeV, according to the measurement by Chadwick, and one ion pair is

formed on the average per 30 eV, the neutrons should have a range of $(5.7 \cdot 10^6/30)$m $\approx$ 200 km if the ionization alone were effective. As the range of a proton of the same energy is about 40 cm (see page 57), and as the ranges are inversely proportional to the square of the charge, according to Equation (47), page 56, the upper limit of the charge of the neutron is 1/700 of the charge of the proton. This proves directly by experiment that the neutron has no charge.

An accurate determination of the neutron mass has to be carried out by means of a nuclear reaction where all the nuclear masses are known, and the reaction energy can be measured. The decomposition of the deuteron by a γ-ray of sufficient energy is best suited for this purpose, i.e., the reaction:

$$^2_1\mathrm{D} + \gamma \rightarrow {}^1_1\mathrm{H} + {}^1_0n$$

Chadwick and Goldhaber showed, long ago, that the energy of γ-rays from RaC (1.8 MeV) is not sufficient to induce the decomposition, whereas the effect could be distinctly observed if the radiation from ThC″ (2.62 MeV) was used. The threshold value for the effect is, therefore, about 2 MeV. This value must equal the binding energy of the deuteron, so that the following mass balance is obtained:

$$M_{\mathrm{D}} + 0.002 = M_{\mathrm{H}} + M_n$$

Using the mass-spectrographic values of M_{D} and M_{H}, the result is $M_n = 1.0090 \pm 0.0005$.

Considerably more accurate values are obtained if attention is not restricted to the determination of the threshold value, but the energy of the protons released by a harder radiation is measured, for example, that of ThC″. The best measurements of this energy in the ionization chamber give (217 ± 11) keV. As the neutron receives the same energy as the proton, and the quantum energy of the γ-radiation is 2.62 MeV, the value obtained for the mass defect of the deuteron is $(2.62 - 2 \cdot 0.217)$ MeV $= (2.19 \pm 0.02)$ MeV or $(2.35 \pm 0.02) \cdot 10^{-3}$ MU. The mass of the neutron is then 1.00895 ± 0.000025. This is also the value included in the tables.

So far, the spin of the neutron has not been directly determined by experiment. Therefore, it cannot be stated with absolute certainty that it is $\hbar/2$. Many indirect indications show, at least, that it is a half-odd multiple of $\hbar$. As the nuclear spin of the deuteron is $\hbar$, and that of the proton $\hbar/2$, there remain for the neutron only the two possibilities, $\hbar/2$ and $^3/_2\,\hbar$, the former of which is, in any case, more probable.

The determination of the magnetic moment is carried out by a procedure similar to the atomic beam method. However, the measurement of the deflection of a neutron beam in a nonhomogeneous magnetic field would presuppose that the beam is as well defined as the atomic beam. This is not possible for neutrons, if only for reasons of intensity. The deflection is, therefore, replaced by the Bloch effect: The absorption of a neutron beam in a magnetic iron plate depends on whether the plate is magnetized parallel or antiparallel to the magnetic moment of the neutrons.

This effect can fairly easily be understood physically. The neutrons are scattered in passing through the iron plate, and there are two such scattering processes: scattering by the nuclei of the iron atoms, and scattering by the electronic shells due to the interaction of magnetic moments. It is essential that the cross sections for both scattering processes be of the same order. This requirement actually holds, because in nuclear scattering a strong force acts in a small volume, and in scattering by the shell a weak force acts

in a large volume. Strictly speaking, the effective cross section is proportional to the square of the matrix element of the potential energy. For a qualitative estimate we can simply say: If U is the mean value of the potential in the region V, V being the volume in which U is noticeably different from zero, then the effective cross section is:

$$\sigma \propto (U_1V_1 + U_2V_2)^2$$

The indices denote the two scattering processes. For the nuclear scattering we can assume: $U_1 = 10$ MeV $\approx 10^{-5}$ erg, $V_1 = (5 \cdot 10^{-13})^3 \approx 10^{-37}$ cm^3, hence $U_1V_1 = 10^{-42}$ erg cm^3. For the second process the atomic volume, $V_2 \approx (10^{-8}\text{ cm})^3 = 10^{-24}$ cm^3, has to be considered as the effective region. The potential energy of the interaction of two magnetic moments, μ_n and μ_{Fe}, is of the order $\mu_n\mu_{\text{Fe}}/r^3$. The moment of the neutron is expected to be of the order of a nuclear magneton (10^{-23} gauss cm^3, see page 19), and as the moment of the iron atom is of the order of a Bohr magneton (10^{-20} gauss cm^3), the result is $10^{-23} \cdot 10^{-20}/10^{-24} = 10^{-19}$ erg and $U_2V_2 = 10^{-43}$ erg cm^3. This is smaller than U_1V_1 only by a factor 10, hence both effects are, indeed, comparable. The magnetic effect means a correction of the order of 20% of the absorption coefficient.

Bloch and Alvarez carried out a precision measurement of the magnetic moment of the neutron. They inserted two iron plates as polarizer and analyzer in the neutron beam and, between the two, they placed a Rabi resonance-beam arrangement consisting of a strong homogeneous magnetic field, H_0, and a weak oscillating magnetic field, H (see page 37). The observations are carried out by means of thermal neutrons because the Bloch effect assumes that the wavelength of the matter wave connected with the neutrons is not small compared to the diameter of the iron atoms. Let μ be the absorption coefficient of the neutrons in the unmagnetized iron plate, $\mu(1 + p)$ in the plate magnetized parallel, and $\mu(1 - p)$ in the plate magnetized antiparallel to the neutrons. If the first plate is magnetized "upwards," that half of the neutrons with moments also pointing "upwards" will be weakened to the fraction $e^{-\mu(1+p)x}$, the other half to the fraction $e^{-\mu(1-p)x}$. In the resonance arrangement, the spins of the neutrons behind the first plate can change their sign with a certain probability, P, so that, for the moment "upwards," we have $\frac{1}{2} e^{-\mu(1+p)x} \times (1 - P) + \frac{1}{2} e^{-\mu(1-p)x} P$ and, for the moment "downwards," $\frac{1}{2} e^{-\mu(1+p)x} P + \frac{1}{2} e^{-\mu(1-p)x} (1 - P)$. These neutrons enter the second iron plate. Their intensities are again decreased by the factors $e^{-\mu(1+p)x}$ and $e^{-\mu(1-p)x}$, respectively. If the intensity was 1 in front of the first plate, the total neutron intensity observed behind the second plate is:

$$I = \left\{\frac{1}{2} e^{-\mu(1+p)x} (1-P) + \frac{1}{2} e^{-\mu(1-p)x} P\right\} e^{-\mu(1+p)x} + \left\{\frac{1}{2} e^{-\mu(1+p)x} P + \frac{1}{2} e^{-\mu(1-p)x} (1 - P)\right\} e^{-\mu(1-p)x}$$

By computing this expression, one obtains:

$$I = e^{-2\mu x}[P + (1 - P) \cosh 2\mu p x]$$

In the measurements of Bloch and Alvarez this intensity was compared with the intensity, I_0, which is obtained by cutting off both magnetic fields so that no change of sign occurs and $P = 0$:

$$I_0 = e^{-2\mu x} \cosh 2\mu p x$$

Thus, one obtains for the observed effect:

$$\frac{I - I_0}{I_0} = - P \frac{\cosh 2\mu px - 1}{\cosh 2\mu px}$$

The "Umklapp" probability is always very small, as explained on page 36, unless the resonance condition of Equation (40), $\mu = \hbar i\omega/H_0$ is satisfied, H_0 being the value of the constant magnetic field and ω the circular frequency of the weak oscillating field. H_0 is varied until a distinct effect is found. The magnetic moment of the neutron follows from this effect.

The effect measured by Bloch and Alvarez is very small; the decrease in the neutron intensity at resonance is not even 2%. But the range of resonance is so narrow that its position can be stated very precisely. The magnetic moment of the neutron is consequently given with the same precision; it is obtained to (1.935 ± 0.02) NM.

Earlier, the sign of the magnetic moment of the neutron was determined by Frisch, v. Halban, and Koch by means of the Bloch effect. In this measurement the neutron beam is again sent through two magnetized iron plates, the polarizer and analyzer. A coil is used to produce a single field, H, between the plates. The field is parallel to the neutron beam and at right angles to the direction of magnetization of the first plate. In this field the neutrons precess with the angular velocity $\omega = \mu H/(\hbar i)$. If the field, i.e, the coil, is of length a, the neutrons having velocity v change their direction by the angle $\varphi = \omega a/v = \mu Ha/(i\hbar v)$. If a is chosen in such a way that, on the average, $\varphi = 90°$ for thermal neutrons, and the analyzer is turned by 90° around the neutron beam as axis, then those neutrons which pass the polarizer with a moment parallel to the direction of magnetization pass the analyzer either parallel or antiparallel, i.e., they are absorbed differently depending upon the direction of precession in the magnetic field. From this experiment the sign μ/i can be determined, and it has been found to be negative.

24. Yield of Nuclear Reactions

Our ideas about the course of a nuclear reaction are essentially based on the description given by Bohr in 1936. Each nuclear reaction is thought of as consisting of two steps. In the first step the projectile is captured by the nucleus, giving rise to a highly excited nucleus which is called *compound nucleus*. As the impinging projectile first hits a particle at the surface of the nucleus, it imparts most of its energy to this particle. This particle hits the constituents farther inside, and so on, so that the energy of the projectile is gradually distributed fairly equally among all the constituents of the nucleus. In a second step this compound nucleus can disintegrate in different ways. A considerable amount of the excitation energy is again concentrated on a surface particle, which is then emitted (proton or neutron emission); or four particles combine to form an α-particle and escape from the nucleus (α-emission); or, finally, the excitation energy is radiated away, and the nucleus goes over into the ground state (capture process). Which of these different possibilities occurs, depends entirely on which process is the most probable in the particular case and, therefore, is most likely to occur before the others.

The reaction probability for the different phenomena depends to a great extent, though not fundamentally, on whether the projectiles employed are slow or fast particles.

1. Cross Section for Fast Projectiles. The cross section of a fast particle for entering the nucleus would approximately equal its geometrical cross section, i.e., $\pi R^2 \sim 10^{-24}$ cm^2, if it were not considerably decreased due to the Coulomb repulsion between projectile and nucleus. The influence of the Coulomb field is best made clear by means of Figure 19, in which the potential in the neighborhood of an atomic nucleus is plotted as a function of the distance, r, from the center of the nucleus. Evidently the energy, E, of a particle coming from the right would be entirely transformed into potential energy at r_0, hence the particle would be slowed down to the radial velocity zero and would have to turn back. It would not reach the nucleus nor could it cause a nuclear reaction, if this conclusion of classical mechanics were more than approximately correct. As is well known, classical mechanics is related to wave mechanics in exactly the same way as geometrical optics to wave optics, the role of the refractive index being taken over by the expression:

$$n = \sqrt{\frac{E - V}{E}}$$

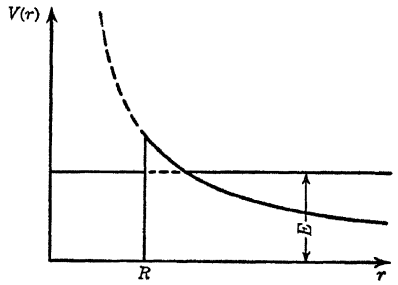


FIG. 19. Potential in the neighborhood of an atomic nucleus. Outside the nuclear radius, R, the slope is measured according to Coulomb behavior. The point r_0 is defined by the intersection of the horizontal line (particles of total energy E) with the potential curve. (In the figure this point is not specially indicated.)

For $r < r_0$, the refractive index is real; for $r > r_0$, however, it becomes imaginary. By the laws of geometrical optics a light ray cannot enter such regions, but by the laws of wave optics this may happen, because the imaginary part of the refractive index becomes simply the absorption coefficient. The wave enters the forbidden region, although, to be sure, it is damped. The matter wave of the incident particle also penetrates the potential barrier. If the barrier is sufficiently low and narrow, the amplitude will not have decreased too greatly on its inner wall, and the particle has a considerable probability of penetrating the barrier (tunnel effect). This probability, which decreases with decreasing velocity, v, of the particle, and increasing atomic number, Z, of the nucleus, as well as z of the particle, was first calculated by Gamow and is, therefore, usually called the Gamow factor, G. We have to include it with πR^2 in the expression for the cross section:

$$\sigma = \pi R^2 G \tag{55}$$

where:

$$G = \frac{\alpha}{e^{\alpha} - 1} \tag{56}$$

with:

$$\alpha = \frac{4zZe^2}{\hbar v}\left\{\arccos\sqrt{x} - \sqrt{x(1-x)}\right\} \tag{57}$$

and:

$$x = \frac{ER}{zZe^2} = \frac{E}{B} \tag{58}$$

Here, E is the kinetic energy of the impinging particle (in the center-of-gravity system), and B the height of the potential barrier at $r = R$. At this point the Coulomb field is to be cut

off, and for $r < R$, an attraction is to act on the impinging particle instead of the Coulomb repulsion. R is essentially identical with the nuclear radius. For small velocities v, α increases and G decreases rapidly. If, however, the velocity becomes large, so that $E = B$ reaches the height of the potential barrier, then $\alpha = 0$ and $G = 1$; the particle can now classically reach the interior of the nucleus. For greater velocities, G must be 1.

The value of the nuclear radius is essential for the numerical result. If the well-tried value:

$$R = 2 \cdot 10^{-13} Z^{1/3} \text{ cm}$$

is used, the following table is obtained, allowing a survey of the effect of the Gamow factor. The energy for which G has one of the given values between 10^{-6} and 1 is given in MeV for protons, deuterons, and α-particles as projectiles. The energy for $G = 1$ is simply identical with the height, B, of the barrier. The auxiliary table contains the corresponding values for the variable, α.

1. ENERGY VALUES FOR PROTONS

$G \backslash Z$	5	10	15	20	30	40	50	60	70	80	90
10^{-4}	0.096	0.29	0.53	0.78	1.34	1.94	2.57	3.2	3.8	4.4	5.1
10^{-3}	0.135	0.39	0.68	1.01	1.68	2.37	3.06	3.8	4.5	5.2	5.8
10^{-2}	0.212	0.57	0.95	1.37	2.18	3.04	3.84	4.7	5.4	6.3	7.0
10^{-1}	0.402	0.94	1.50	2.07	3.10	4.15	5.16	6.1	7.0	7.9	8.9
1	2.12	3.37	4.41	5.34	7.00	8.47	9.85	11.1	12.3	13.5	14.5

2. ENERGY VALUES FOR DEUTERONS

$G \backslash Z$	5	10	15	20	30	40	50	60	70	80	90
10^{-4}	0.15	0.43	0.76	1.10	1.84	2.57	3.30	4.0	4.8	5.5	6.2
10^{-3}	0.21	0.57	0.96	1.38	2.18	3.05	3.88	4.7	5.4	6.3	7.1
10^{-2}	0.31	0.78	1.26	1.76	2.74	3.64	4.69	5.6	6.5	7.3	8.1
10^{-1}	0.55	1.22	1.85	2.50	3.69	4.47	5.59	6.9	7.8	8.9	9.7
1	2.12	3.37	4.41	5.34	7.00	8.47	9.85	11.1	12.3	13.5	14.5

3. ENERGY VALUES FOR α-PARTICLES

$G \backslash Z$	5	10	15	20	30	40	50	60	70	80	90
10^{-4}	0.70	1.71	2.74	3.84	5.86	7.90	9.8	11.7	13.5	15.2	16.8
10^{-3}	0.89	2.08	3.23	4.46	6.66	8.79	10.8	12.8	14.7	16.5	18.3
10^{-2}	1.19	2.61	3.88	5.28	7.70	9.97	12.2	14.2	16.2	18.2	20.0
10^{-1}	1.76	3.50	5.07	6.55	9.27	11.80	14.2	16.4	18.5	20.7	22.7
1	4.23	6.74	8.83	10.69	14.00	16.94	19.7	22.2	24.6	26.9	29.1

AUXILIARY TABLE

G	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1
α	16.63	14.16	11.67	9.12	6.48	3.62	0

The cross section for a particle entering an atomic nucleus can thus be roughly calculated. It still has to be modified by the *resonance phenomena* which were observed quite early by Pose.

If energy and momentum are to be conserved for the compound nucleus, then a particle of any indefinite energy cannot possibly be captured. By the law of conservation of momentum, the part $(m/M)E$ of the kinetic energy, $E = mv^2/2$, of the impinging particle is

imparted to the center of gravity of the compound nucleus of mass M, whereas the principal part:

$$Q = E\left(1 - \frac{m}{M}\right)$$

is converted into its inner excitation energy. If the binding energy of the captured particle to the atomic nucleus equals U, $Q - U$ is the excitation energy of the compound nucleus above its ground state. As it is a quantized system, only certain values of the excitation energy, $Q - U$, are allowed, i.e., capture without radiation can take place only for certain values of the kinetic energy, E, of the incident particles, i.e., only for the "*resonance energies.*"

This situation is somewhat eased on account of the short lifetime of the compound nucleus. If, after a time, Δt, it disintegrates into any structural parts, its excitation energy fundamentally can be measured only with the uncertainty, ΔE, that follows from Heisenberg's uncertainty relation:

$$\Delta E \cdot \Delta t = \hbar$$

Therefore, the law of conservation of energy does not have to be satisfied quite accurately for the compound nucleus; resonance levels are formed of the finite width, $\hbar/\Delta t$.

In general, the following rules can be set up: The lifetime of the compound nucleus becomes shorter, and, consequently, the resonance levels wider with increasing excitation energy. With increasing weight and excitation energy of the nucleus the levels approach each other more closely. This is the reason why, for nuclei of medium weight and excitation energies of about 12 MeV, the spacing of the terms is less than the width of the individual terms. In other words: In this case no resonance phenomena are observed, but rather a continuum. For light nuclei and excitation energies of this order of magnitude, the spacing of the levels is of the order of 10 to 100 keV, and the level width lies between 1 and 10 keV. In fact, Fünfer and, subsequently, other scientists, by closer investigation succeeded in resolving the yield curves from light nuclei into the contributions of many such levels.

If the gaps between the different resonance levels cannot be resolved, they cause a considerable apparent reduction of the cross section compared to Equation (55). It follows from very general principles that the cross section for the formation of the compound nucleus for resonance energies cannot become larger than λ^2/π, i.e., not larger than $h^2/2\pi mE$, as long as the De Broglie wavelength, $\lambda = h/mv$, of the incident particle is larger than $2\pi R$. This means, numerically, that for protons and neutrons:

$$\sigma_{\max} = \frac{2.63 \cdot 10^{-24}\ \text{cm}^2}{E\ (\text{MeV})}$$

if this is $> 4\pi R^2$, and $^1/_4$ of this value for α-particles.

The compound nucleus can then disintegrate spontaneously in different ways. For every possibility of disintegration there exists, as in radioactivity, a mean life, τ, a decay constant, $\lambda = 1/\tau$, or, according to the uncertainty relation, a corresponding level width, $\Gamma = \hbar\lambda$. The order of magnitude obtained for the mean life for the various possibilities of decay is as follows: The mean life for the transition to a lower state or to the ground state by γ-radiation is about 10^{-14} sec if the excitation energies are a few MeV. It is about 10^{-17}

sec for the emission of a neutron of several MeV, provided that this process is energetically possible. The probability for the emission of a slower neutron is smaller, and is proportional to the velocity assumed by the neutron after it has left the nucleus. Values of the same order hold for protons and α-particles, but, in this case, the Gamow factor has to be added to the decay constant and the mean life can be considerably increased.

The process which actually occurs is, naturally, always the one with the highest decay constant and the shortest lifetime, as it anticipates the other possibilities of disintegration. Consequently, the *capture process* proper, with the excess energy of the compound nucleus radiating away, is of little importance where fast particles are concerned. A particle is almost always emitted from the compound nucleus, and usually the probability for the emission of a neutron is greater than for the emission of a charged particle that has to penetrate another potential barrier when it escapes from the nucleus. In heavy nuclei, processes in which charged particles are emitted do not occur at all.

An exception to this rule is the capture of protons $(p\ \gamma)$, which is quite frequently observed. As the reaction $(p\ n)$ is endothermic, the only competing process is $(p\ \alpha)$, in addition to ordinary scattering $(p\ p)$. An increase of the Gamow factor up to 10^{-3} is sufficient to make the reaction $(p\ \gamma)$ just as probable as $(p\ \alpha)$.

For light nuclei the Gamow factor is of little importance. It often happens that not all of the excess energy of the compound nucleus is transformed into kinetic energy of an emitted particle. A slower particle is thus emitted, leaving behind an excited nucleus which only subsequently goes over into the ground state by γ-radiation. Consequently, several range groups of protons or α-particles are observed in the case of light particles.

A special case is the reaction $(d\ p)$. A nucleus is bombarded by a deuteron; the proton contained in it is repulsed by the Coulomb field surrounding the nucleus, but the neutron is not. The deuteron approaching the nucleus will be increasingly "polarized," because the proton remains behind the neutron. Actually, the same effect should also take place in the case of the α-particle. As the α-particle is very closely bound, the deuteron only very loosely, the polarization of the α-particle can be neglected, whereas in the case of the deuteron the polarization increases the probability—compared to the simple Gamow theory—for the neutron to enter the nucleus, leaving the proton behind. This effect was first studied by Oppenheimer and Philipps. If $E_d = 2.19$ MeV denotes the binding energy of the deuteron and E its kinetic energy, the polarization affects the yield quantitatively in such a way that a function, $F(E/E_d)$, is included as a factor of the quantity α, Equation (57). Some of the values it assumes are:

$E/E_d =$	0.0	0.5	1.0	1.5	2.0
$F(E/E_d) =$	1.00	0.495	0.355	0.250	0.189

This correction of the Gamow theory holds, however, only for the reaction $(d\ p)$, not, e.g., for $(d\ n)$. For this process it is necessary also for the proton to enter the nucleus.

2. Cross Section for Slow Projectiles. Particles of less than approximately 100 keV energy can reach even a light atomic nucleus only if they are uncharged. Consequently, neutrons with even an arbitrarily small energy are the only projectiles able to transmute atomic nuclei. The compound nucleus is formed in this case by the combining of the neutron with the nucleus. Since the binding energy between neutron and nucleus lies between 8 and 9 MeV and is fairly constant for the whole periodic system the compound nucleus is excited above its ground state by this amount of energy. The energy levels of

the light nuclei are separated by 10 to 100 keV for such an excitation energy, whereas for nuclei with masses between 100 and 200 they are spaced from only a few eV up to 100 eV.

In this case also, the width of the levels is determined by the various possibilities of disintegration of the compound nucleus. Protons cannot be emitted because of the endothermic character of the reaction $(n\,p)$. Even α-particles can be emitted only in a few cases; in general, the reaction $(n\,\alpha)$ is also endothermic, or at least exothermic to such a low degree that the Gamow factor very strongly impedes the ejection of α-particles. Hence, only the two possibilities $(n\,n)$ (scattering) and $(n\,\gamma)$ (capture) remain. We have previously seen that the decay constant of the compound nucleus for $(n\,n)$ with neutron energies of a few MeV is about 10^{17} sec^{-1} and is proportional to v. For the thermal neutron energy of $^1/_{30}$ eV, then, it is only 10^{13} sec^{-1}, corresponding to a level width of about 0.01 eV. For an energy of $^1/_{30}$ eV, the process $(n\,\gamma)$ with its decay constant of 10^{14} sec^{-1} is, therefore, about ten times as probable as the scattering process and gives a level width of about 0.1 eV.

The only process for slow neutrons occurring to a considerable extent should, therefore, be the capture process $(n\,\gamma)$, apart from a few exceptions. It should show a strongly marked resonance character, as the level width of the order 0.1 eV is much smaller than the distances between the levels, which amount certainly to a few eV for the heaviest nuclei.

In the production of slow neutrons (see page 53), a predominant amount is always obtained in the region of thermal energies (about $^1/_{30}$ eV), and, in addition, a slowly decreasing but still marked intensity up to about 100 eV. A considerable yield of the $(n\,\gamma)$-process can, therefore, be expected from slow neutrons if one or more resonance levels fall in this energy region, and an extremely high yield if, by chance, a resonance level lies in the thermal region. This is very unlikely for light atomic nuclei, owing to the large spacing of the levels. Consequently, the capture process $(n\,\gamma)$ does not occur here. In nuclei with mass numbers of 50 and more, the levels lie close enough to make capture possible for almost every nucleus. Hence, the reaction $(n\,\gamma)$ is one of the most frequent and has been thoroughly studied up to the heaviest nuclei.

In some light nuclei, particularly ^{6}Li and ^{10}B, the reaction $(n\,\alpha)$ is strongly exothermic. The compound nucleus then has a very considerable α-decay probability, which produces an abnormal widening of the level. These nuclei have, therefore, a very considerable cross section for the reaction $(n\,\alpha)$, even in the thermal region: ^{6}Li has a cross section of about 900, and ^{10}B of about $3000 \cdot 10^{-24}$ cm^2. These numbers are higher than the geometrical nuclear cross section by several powers of ten, but they are still below the theoretical limit, λ^2/π.

Moon and Tillman were the first to detect experimentally the existence of resonances in the region of slow neutrons by means of a procedure known from optics, the "self-reversal" of the resonance line. If, e.g., slow neutrons are filtered through a silver foil, a definite energy range is selected, namely, the neighborhood of the resonance energy. If the neutrons are detected by inducing the reaction $(n\,\gamma)$ in a second silver sheet* (the indicator), which has been placed behind the foil, a much smaller number of neutrons is registered in the indicator because it responds directly to that energy range in which the filter absorbs strongly. If, however, a copper sheet is used as indicator, the decrease in intensity is much smaller because copper responds to another energy range.

The classical arrangement for the measurement of the resonance energy was devised

* In the reaction $(n\,\gamma)$, β-active silver is formed and its radioactivity can be measured.

by Weekes, Livingston, and Bethe. Filters of boron and cadmium are inserted in four different ways between the substance whose resonance energy is to be measured, e.g., silver, and the source of the slow neutrons. The intensity is measured (I) without filter, (II) with a boron filter only, (III) with a cadmium filter only, and (IV) with both a boron and a cadmium filter. Thus, use is made of the characteristic properties of boron and cadmium: The cross section, hence the absorption coefficient, for the absorption of slow neutrons by boron in the previously mentioned $(n\ \alpha)$-process is inversely proportional to the velocity of the neutrons. Cadmium, however, has a resonance level in the thermal region; hence, even a thin layer absorbs the neutrons completely, but is practically transparent to those above a few tenths eV. By filtering through cadmium, the thermal neutrons are, therefore, suppressed and the behavior of only the resonance neutrons is investigated. In experiment (I) the sum of the primary intensities, I_0 and I_0', of thermal and fast neutrons, respectively, are measured, and in experiment (II) the sum of the intensities I_1 and I_1', which have been decreased by absorption in boron, where $I_1 = I_0 e^{-\mu_{\text{th}} d}$, $I_1' = I_0' e^{-\mu_{\text{res}} d}$ (d = thickness of boron layer). In experiments (III) and (IV) the thermal intensity is suppressed by the cadmium sheet, and only I_0' and I_1', respectively, are measured. The absorption coefficient of thermal neutrons in boron, μ_{th}, can, therefore, be determined from the combination:

$$\frac{\text{II} - \text{IV}}{\text{I} - \text{III}} = I_1/I_0 = e^{-\mu_{\text{th}} d}$$

In the same way the absorption coefficient, μ_{res}, of the resonance neutrons of the indicator substance (in our case, silver) in boron follows from the combination:

$$\text{IV}/\text{III} = I_1'/I_0' = e^{-\mu_{\text{res}} d}$$

As these absorption coefficients are inversely proportional to the velocities:

$$\mu_{\text{th}}/\mu_{\text{res}} = v_{\text{res}}/v_{\text{th}}$$

the velocity, hence the energy, of the resonance neutrons (of silver) can be calculated from the known mean velocities of thermal neutrons (2500 m/sec at room temperature).

A clear result regarding the width of the resonance lines is much more difficult to obtain. To a certain extent an experimental possibility is presented by the partial overlapping of the levels of two different elements, e.g., rhodium and iridium, which is expressed by the fact that the neutron intensity, as measured by an Ir-indicator, is decreased by a Rh-filter to approximately the same extent as by an Ir-filter. For more precise statements, the theoretical formula for the cross section (or the absorption coefficient) as a function of the energy in the neighborhood of a resonance level has to be used. This formula was obtained by Breit and Wigner using a kind of dispersion theory of the neutron waves:

$$\sigma = \frac{\lambda^2}{\pi} \frac{\Gamma_n \Gamma_\gamma}{(E - E_r)^2 + (\Gamma/2)^2} \tag{59}$$

λ is the wavelength of the De Broglie wave of the incident neutrons. Γ_n is the level width with respect to the process $(n\ n)$ and Γ_γ the width with respect to $(n\ \gamma)$. Γ_γ is independent of the energy, but Γ_n is proportional to v, according to the foregoing. The denominator has a resonance point at $E = E_r$; hence, E_r is the resonance energy. The damping constant is $\Gamma = \Gamma_n + \Gamma_\gamma$; hence it is proportional to the probability of total decay for the level. For small velocities, $\Gamma_n \ll \Gamma_\gamma$, so that Γ can be replaced by Γ_γ, which is independent of the

energy. As λ is proportional to $1/v$, the formula can be brought into the following form:

$$\sigma = \sqrt{\frac{E_r}{E}} \frac{\sigma_r \left(\frac{\Gamma}{2}\right)^2}{(E - E_r)^2 + \left(\frac{\Gamma}{2}\right)^2} \tag{60}$$

In the region far to the left of the resonance position (i.e., mostly in the thermal region), the cross section is proportional to $1/v$. To the right of the resonance position, it falls off rapidly with $1/v^5$. If absorption measurements are carried out with the use of the same element as filter and indicator, both with and without cadmium filter, the absorption coefficient and, hence, the cross section for the center of the line, σ_r, and for thermal neutrons, σ_{th}, can be determined experimentally. Since the quantity, E_r, can also be measured, the line width, Γ, remains the only unknown quantity in Equation (60). If $E_r \gg kT$ and $E_r \gg \Gamma/2$, which is almost always the case, one can write:

$$\sigma_{\text{th}} = \sqrt{\frac{E_r}{kT}} \frac{\sigma_r \left(\frac{\Gamma}{2}\right)^2}{E_r^2} \tag{61}$$

and Γ can be calculated from this equation.

25. Survey of Known Types of Reactions. Fission of the Heaviest Nuclei.

The main group of reactions consists of those processes in which a particle falls on the nucleus, forming a compound nucleus, and a different particle leaves the nucleus. So far the projectiles used for this purpose have been: neutron, proton, deuteron, α-particle, and recently, also, the nucleus, ^{3}He, in a few cases. Neutrons, protons, and α-particles occur as fragments. The deuteron practically never occurs as a fragment because it is easily split into proton and neutron, owing to its small binding energy. Thus, the emission of one of these two particles with a correspondingly higher energy is more probable. Moreover, the reactions $(n\ d)$ and $(p\ d)$ are endothermic, with an average energy of 6 MeV. The reaction $(p\ n)$ is also always endothermic, and the reaction $(n\ p)$ mostly so, though not very strongly (see page 68).

All reactions of this kind may be followed by radiation if the residual nucleus is left in an excited state after the emission of a particle. In this case the emission of particles of smaller energy and range is observed than corresponds to the reaction energy for the transition to the ground state of the final nucleus. The observation of such range groups is a valuable source of information regarding the position of excited terms.

Another important group are those reactions in which γ-radiation does not occur as an occasional secondary process, but is part of the main process. These are, first of all, the capture processes, particularly $(n\ \gamma)$ for slow neutrons and $(p\ \gamma)$ in a number of nuclei. The reverse of the first reaction, the nuclear photodissociation $(\gamma\ n)$, which was discovered by Bothe and Gentner, is also known in many nuclei. The required γ-energy must at least equal the dissociation energy of the neutron, i.e., about 8 MeV for most nuclei. The dissociation energy is much smaller (about 2 MeV, see page 11) only for ^{2}D and ^{9}Be. The process (γ, p) has not been observed as yet. This is probably due to the infrequent occurrence of photodissociation in light nuclei, and in heavy nuclei the ejection of a proton is so

strongly impeded by the Gamow barrier that it is anticipated by a neutron, and the reaction $(\gamma\, n)$ takes place. The cross section for $(\gamma\, n)$ is usually of the order 10^{-28} cm^2.

The process $(n, 2n)$, a reaction with the same resulting nucleus as $(\gamma\, n)$, was first discovered by Heyn. This process, too, occurs only if the incident neutron has an energy of at least 8 MeV. Correspondingly, the occurrence of reactions with the emission of several particles is to be expected only for high projectile energies. The reaction $(n, 3n)$ can thus occur only above a neutron energy of about 16 MeV. The reaction (n, pn) should have the same threshold energy as $(n, 2n)$. The threshold energy of $(n\, d)$ should be less by the binding energy of the deuteron, i.e., about 6 MeV (see above). For the case of a very high energy of the incident particle (about 100 MeV), a great many neutrons and protons are emitted by the nucleus. If we think of the nucleus as a liquid drop, this process can be described intuitively as a kind of "vaporization." Although such transmutations cannot be produced artificially in the laboratory by technical means, they can be induced by the fast particles of cosmic rays. They were first observed in the form of "bursts" by Blau and Wambacher, who found numerous proton tracks, originating in one point, in photographic layers which had been exposed to cosmic rays at great height for some length of time.

In a systematic description of nuclear reactions, those in which projectile and outgoing particle are of the same type must finally be mentioned. In this case one speaks of scattering rather than of a reaction. An essential feature is that the individuality of the particle is destroyed if scattered by an atomic nucleus. The particle is absorbed and hence becomes indistinguishable from the other particles of the atomic nucleus, one of which is again emitted. The scattering is called elastic or inelastic according to whether the emitted particle has the same energy as the projectile (diminished by the energy transferred to the center of gravity of the nucleus according to the law of conservation of momentum), or a smaller energy. In the latter case the residual nucleus remains in an excited state. Reactions of this nature are usually very difficult to observe and, therefore, they are little known although they should occur frequently. In a few cases they have been found to be of particular interest.

An altogether new type of reaction in the heaviest atomic nuclei was discovered in 1939 by Hahn and Strassmann when studying the so-called "transuranic" elements (which were found to be nonexistent). According to the mass defects, a disintegration of the heaviest nuclei into two moderately heavy nuclei—e.g., of ${}^{238}_{92}$U into ${}^{98}_{36}$Kr and ${}^{140}_{56}$Ba—should be strongly exothermic, with a reaction energy of 150 to 200 MeV, as the binding energy per nuclear constituent has a maximum for nuclei of medium mass number. This disintegration does not occur spontaneously because the splitting atomic nucleus has to pass first through a stage of elongation, then through one in which it is pinched in. This shape is energetically less favorable than the initial spherical shape. An "activation energy" is, therefore, necessary in order to bring the nucleus over the potential barrier and to start the disintegration. For the heaviest nuclei this barrier is only a few MeV, so that the capture of one neutron of this energy is sufficient to induce the fission process. In nuclei heavier than uranium, even this small activation energy would be unnecessary, and the fission would take place spontaneously. This seems to be the reason why $Z = 92$ is the last element in the periodic system.

The height, V_{max}, of the threshold potential which has to be overcome, compared to the ground state of the compound nucleus, was calculated by Bohr and Wheeler, based on the conception of the atomic nucleus as a liquid drop. The energy content of such a drop-

let increases with the deformation due to the increase in surface (surface tension, see page 100); it simultaneously decreases due to the decreasing Coulomb repulsion of the nuclear protons which are then farther apart. The competition of these two phenomena gives quantitatively the magnitude of the potential barrier in MeV:

$$V_{\max} = \{10.18\,(1 - x)^3 - 4.62(1 - x)^4\}A^{2/3} \tag{62}$$

where A is the mass number of the compound nucleus, and

$$x = 0.0209\,Z^2/A \tag{63}$$

for the indicated compound nucleus.

If fission is produced by neutrons, the compound nucleus is obtained from the initial nucleus by adding one unit to the mass number. For this case—so far the only important one—the Bohr-Wheeler function has been tabulated in the accompanying table, and $V_{\max}$ is given in MeV for a few heavy nuclei.

Initial nucleus	x	$V_{\max} A^{-2/3}$	$V_{\max}$	Initial nucleus	x	$V_{\max} A^{-2/3}$	$V_{\max}$
$^{183}_{74}$W	0.624	0.449	14.6	$^{230}_{96}$Io	0.735	0.187	7.1
$^{189}_{76}$Os	0.636	0.410	13.5	$^{232}_{90}$Th	0.729	0.200	7.6
$^{195}_{78}$Pt	0.649	0.370	12.5	$^{231}_{91}$Pa	0.747	0.163	6.2
$^{201}_{80}$Hg	0.664	0.327	11.3	$^{234}_{92}$UII	0.753	0.152	5.8
$^{207}_{82}$Pb	0.676	0.295	10.4	$^{235}_{92}$AcU	0.750	0.157	6.0
$^{226}_{88}$Ra	0.714	2.35	8.8				
$^{227}_{89}$Ac	0.726	2.07	7.8	$^{238}_{92}$UI	0.740	0.177	6.8

Thus, by addition of a neutron, a compound nucleus with an excitation energy greater than $V_{\max}$ has to be produced in order to obtain fission. The minimum kinetic neutron energy required is $E = V_{\max} - U$, U being the binding energy of the neutron to the nucleus, which for most nuclei lies at about 8 MeV. It is somewhat smaller only for the very heaviest nuclei (beyond lead, in the accompanying table beyond Ra), about 6.4 MeV for initial nuclei of an odd, and about 5.4 MeV for initial nuclei of an even neutron number. Evidently, fission by fast neutrons of a few MeV ought to be possible in all nuclei included in the table, and so far, indeed, it has been detected in the investigated nuclei of Io, Th, Pa, UI. But fission by slow (thermal) neutrons should be possible only in the single case of AcU. Fission was actually discovered by Hahn and Strassmann in uranium by means of thermal neutrons. Later, Nier and his collaborators proved by irradiating the uranium isotopes separated in the mass spectrograph with neutrons, that this reaction takes place in the rare isotope ^{235}U, and not in the much more abundant ^{238}U. The cross section for fission by fast neutrons is of the order of 10^{-25} cm^2 in all investigated elements. The fission cross section in the pure isotope ^{235}U for slow neutrons is inversely proportional to their speed, and for thermal neutrons is of the order of $3 \cdot 10^{-22}$ cm^2.

If fission takes place, two heavy fragments are formed with masses about 95 and 140 respectively. The energy of the lighter fragments (mass about 95) is approximately 90 MeV, and their range in air approximately 1.5 cm. The energy of the heavier fragments (mass about 140) is smaller, according to the law of conservation of momentum, and lies

at about 60 MeV; their range is greater, about 2.1 cm. These heavy fragments could be decomposed chemically into a great many different isotopes. So far, the following elements have been detected with certainty as fragments of uranium:

In the light group: $_{35}$Br, $_{36}$Kr, $_{37}$Rb, $_{38}$Sr, $_{39}$Y, $_{40}$Zr, $_{41}$Nb*, $_{42}$Mo, 43
In the heavy group: $_{57}$La, $_{56}$Ba, $_{55}$Cs, $_{54}$Xe, $_{53}$I, $_{52}$Te, $_{51}$Sb

All these substances are β-radioactive, owing to their large excess of neutrons. Most of these, quite certainly, are not primary products in the fission, but are produced by subsequent β-disintegration. According to up-to-date chemical results the following elements are primary products: In the light group at least one Br-isotope, three Kr-isotopes, and probably two Mo-isotopes; in the heavy group three Sb-isotopes, three Te-isotopes, three Xe-isotopes, and one Ba-isotope.

If the heavy nucleus breaks into only two fragments, the sum of their charge and mass numbers must, of course, equal charge and mass number of the compound nucleus. Since two to three neutrons with energies of a few MeV also split off in fission, the mass balance is, of course, violated. Charged particles, however, do not seem to be split off, hence the charge balance must hold. From each primary fragment the charge number of its partner can, therefore, be obtained, though not the mass number.

Data on the fragments are included in the table, as far as they can be given now.

* Niobium = columbium.

III. UNSTABLE NUCLEI

26. Natural Radioactivity

It is well known that natural radioactivity was discovered by Becquerel and by Marie and Pierre Curie in the heaviest elements of the periodic system, i.e., thorium and uranium, by means of the ionization produced by the emitted rays. Soon afterward, three different types of radiation, which can be separated by their quite different penetrabilities, were distinguished. These rays are called α-, β-, and γ-rays, and the following is what is known about them today:

α-rays are helium nuclei of the isotope ^{4}He. Their energy is usually approximately a few MeV. Each α-active atomic nucleus emits α-particles of definite energy and range. It may happen that weak groups of somewhat larger or smaller range appear, owing to the fact that the initial or final nucleus of the α-decay is in an excited state. This phenomenon is, however, of little importance.

β-rays are electrons whose energies are spread out into a continuum with an upper limit of a few MeV, and often only of a few hundred keV.

γ-rays are a wave radiation, i.e., photons with a minimum energy, $h\nu$, of 100 keV and a maximum energy for naturally radioactive elements of 2.62 MeV. γ-radiation is not radioactivity in the proper sense, but should be understood as a subsequent process caused by the excited state of the residual nucleus. It is the reason for the so-called secondary β-rays ("internal conversion" electrons), i.e., electrons which are ejected by γ-radiation from atomic shells through photoelectric effect. The γ-rays and secondary β-rays have line spectra. A γ-radioactivity in its proper sense was discovered only three years ago (isomerism, see page 93).

The naturally radioactive nuclei emit either α-rays or β-rays. In only a few cases—namely, the branching points of the radioactive series at RaC, ThC, and AcC, and the recently discovered one at Ac—the same nucleus may happen to emit α- and β-rays. In all these occurrences a certain definite ratio of branching can be stated; for example, 65% of all ThC-nuclei disintegrate by β-emission into ThC′ and 35% of all ThC-nuclei disintegrate by α-decay into ThC″.

Radioactive decay takes place according to purely statistical laws, i.e., the probability for a decay is the same during each element of time, say $\lambda\, dt$. Out of N radioactive nuclei which are present at the time t, the number of nuclei disintegrating in the time interval dt is:

$$-dN = N\lambda\, dt$$

If this differential relation is integrated, one obtains:

$$N = N_0 e^{-\lambda t} \tag{64}$$

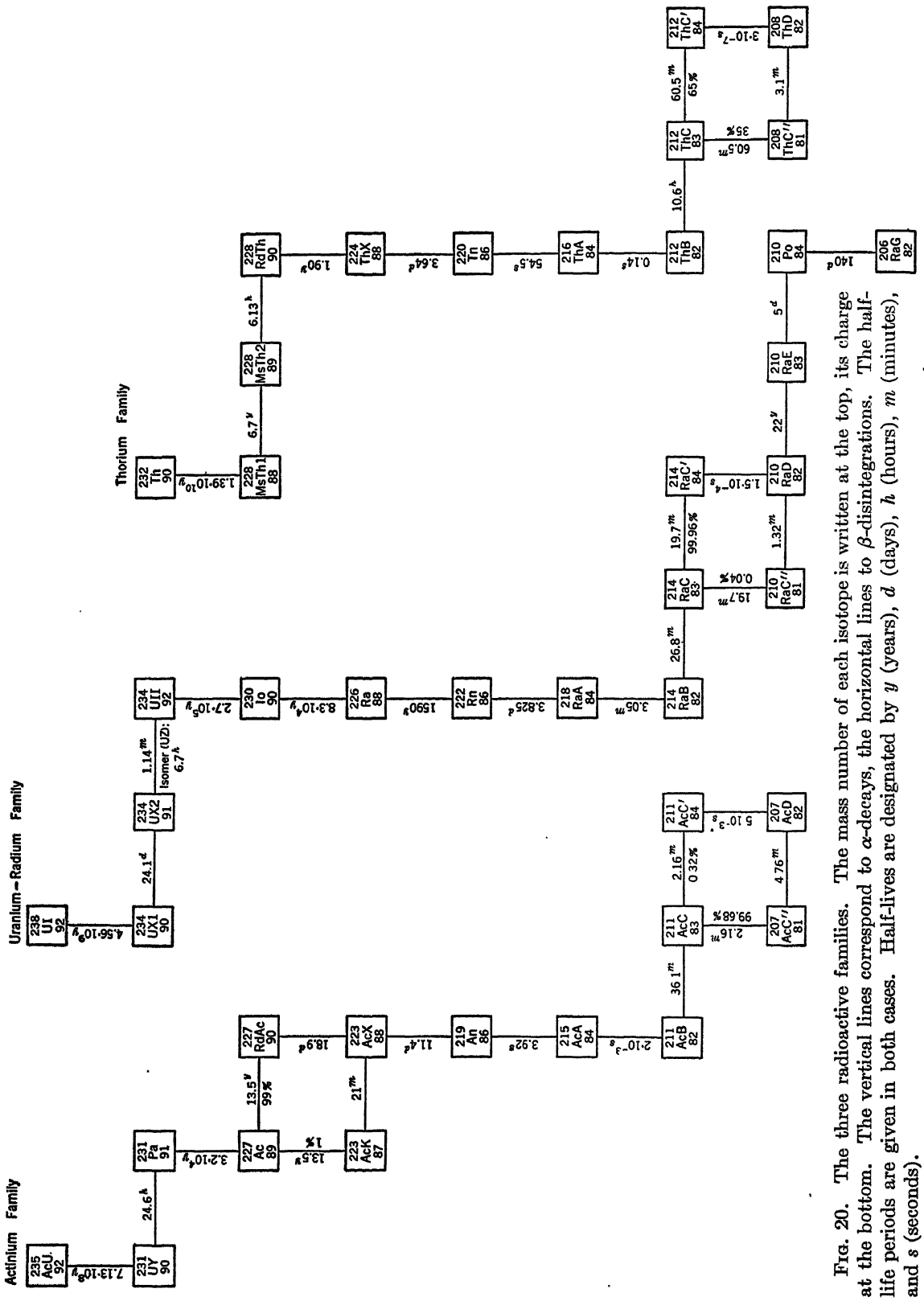


FIG. 20. The three radioactive families. The mass number of each isotope is written at the top, its charge at the bottom. The vertical lines correspond to α-decays, the horizontal lines to β-disintegrations. The half-life periods are given in both cases. Half-lives are designated by y (years), d (days), h (hours), m (minutes), and s (seconds).

the well-known law of radioactive decay. The quantity observed is generally not the number of surviving nuclei, but the number decaying per unit of time:

$$a = \lambda N \tag{65}$$

This quantity is usually called activity. It decays, of course, also exponentially.

The quantity, λ, is called decay constant. It gives the probability of decay per unit of time. Its reciprocal value is designated as mean life. The time, T, during which the activity is reduced to one-half:

$$T = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \tag{66}$$

is called the half-value period or half-life period of the decay. Often the name is abbreviated to "period."

The naturally radioactive substances are not directly converted into stable final products, but form the so-called radioactive families. These are long chains in which each element is produced by radioactive decay of its predecessor. Three such families are distinguished: The uranium-radium family, the thorium family, and the actinium family. Figure 20 shows the succession of the various decays in the three families and gives their half-life periods.

If a particular substance is separated from such a series by chemical means, it will again produce, after some time, all the disintegration products formed from it. If one waits long enough, an equilibrium will be established. The same number of nuclei of each disintegration product is formed and disintegrates per unit of time as the number of nuclei of its parent decaying per unit of time, provided that the parent is much more long-lived than its disintegration products. The activities of the parent substance and all its disintegration products then equal each other:

$$\lambda_1 N_1 = \lambda_2 N_2 = \lambda_3 N_3 = \ldots = \lambda_k N_k \tag{67}$$

Thus, the amounts of nuclei present are inversely proportional to their decay constants, or directly proportional to their half-life periods. The amount of radium contained in 1 g uranium from uranium-bearing minerals can thus be calculated. As the half-life period of uranium is $4.56 \cdot 10^9$ years, that of radium about $1.6 \cdot 10^3$ years, and the atomic weights 238 and 226, respectively, 1 g uranium contains:

$$\frac{226}{238} \cdot \frac{1.6 \cdot 10^3}{4.56 \cdot 10^9}\, g = 0.33 \cdot 10^{-6} \text{ g radium}$$

One ton of uranium contains, therefore, about $^1/_3$ g radium. Substances of even shorter half-life periods of only a few days cannot, therefore, be produced in weighable amounts.

The rise and decay with time of the activity of the disintegration products can always be computed from a system of simple differential equations. Assume that at the time $t = 0$ the amount, N_1^0, be separated from substance 1, and that no disintegration products 2, 3, etc., be present. If λ_1, λ_2, λ_3, etc., are the decay constants, N_1, N_2, N_3, etc., the numbers of nuclei of different types present at the time t, the following equations hold:

$$\begin{aligned} dN_1/dt &= -\lambda_1 N_1 \\ dN_2/dt &= -\lambda_2 N_2 + \lambda_1 N_1 \\ dN_3/dt &= -\lambda_3 N_3 + \lambda_2 N_2, \text{ etc.} \end{aligned}$$

The solution of this system of differential equations, with the given initial conditions, is as follows:

$$\left.\begin{aligned} N_1 &= N_1^0 e^{-\lambda_1 t} \\ N_2 &= N_1^0 \frac{\lambda_1}{\lambda_2 - \lambda_1} \left\{ e^{-\lambda_1 t} - e^{-\lambda_2 t} \right\} \\ N_3 &= N_1^0 \frac{\lambda_1 \lambda_2}{(\lambda_1 - \lambda_2)(\lambda_2 - \lambda_3)(\lambda_3 - \lambda_1)} \left\{ (\lambda_3 - \lambda_2) e^{-\lambda_1 t} + (\lambda_1 - \lambda_3) e^{-\lambda_2 t} + (\lambda_2 - \lambda_1) e^{-\lambda_3 t} \right\}, \text{etc.} \end{aligned}\right\} \quad (68)$$

The corresponding activities are obtained by multiplication with the decay constants, λ_1, λ_2, λ_3, respectively.

Frequently, the half-life period is the means best suited to recognize easily a particular radioactive substance. The decay energy is often physically more interesting. In β-decay, it is equal to the upper limit of the energy of the decay electrons, except for a possibly accompanying γ-radiation (see page 83). In α-decay, it does not equal the kinetic energy of the emitted α-particle, but has to be increased by the energy with which the nucleus recoils in the decay. If Q is the energy of decay and E_α the energy of the α-particle escaping from a nucleus of mass number A, it follows from the equality of the opposite momenta of α-particle and recoil nucleus that:

$$Q = E_\alpha \left(1 + \frac{4}{A - 4}\right) = \frac{A}{A - 4} E_\alpha \quad (69)$$

The knowledge of the decay constant can be used to calculate with considerable precision the difference of the mass defects of the heaviest nuclei. This is best made clear by an example:

Radium disintegrates into radon by α-decay, with an energy of disintegration Q = 4.88 MeV = $5.25 \cdot 10^{-3}$ MU. Let the radium nucleus have a mass defect D_{Ra}. As it consists of 88 protons and 138 neutrons, its mass is:

$$M_{\text{Ra}} = 88\, M_p + 138\, M_n - D_{\text{Ra}}$$

In the same way the mass of the radon nucleus, consisting of 86 protons and 136 neutrons, is:

$$M_{\text{Rn}} = 86\, M_p + 136\, M_n - D_{\text{Rn}}$$

The difference of the two is given by the mass lost, i.e., the mass of the α-particle:

$$M_\alpha = 2\, M_p + 2\, M_n - D_\alpha$$

and the mass converted into kinetic energy, i.e., Q/c^2. Hence:

$$M_{\text{Ra}} - M_{\text{Rn}} = 2\, M_p + 2\, M_n - D_{\text{Ra}} + D_{\text{Rn}}$$

and:

$$M_\alpha + Q/c^2 = 2\, M_p + 2\, M_n - D_\alpha + Q/c^2$$

are equal to each other:

$$D_{\text{Ra}} - D_{\text{Rn}} = D_\alpha - Q/c^2$$

The mass defect of the α-particle is well known, being equal to $30.32 \cdot 10^{-3}$ MU. The quan-

tity, Q/c^2, is the energy of disintegration measured in the mass scale, hence $5.25 \cdot 10^{-3}$ MU. Consequently:

$$D_{\mathrm{Ra}} - D_{\mathrm{Rn}} = 30.32 - 5.25 = 25.07 \cdot 10^{-3}\ \mathrm{MU}$$

is the difference between the mass defects of radium and radon.

One can, in principle, proceed by the same scheme for the β-active elements. In this manner the mass defects of all nuclei of one family are obtained, apart from a common additive constant, which cannot be stated with the same precision. This constant can be deter-

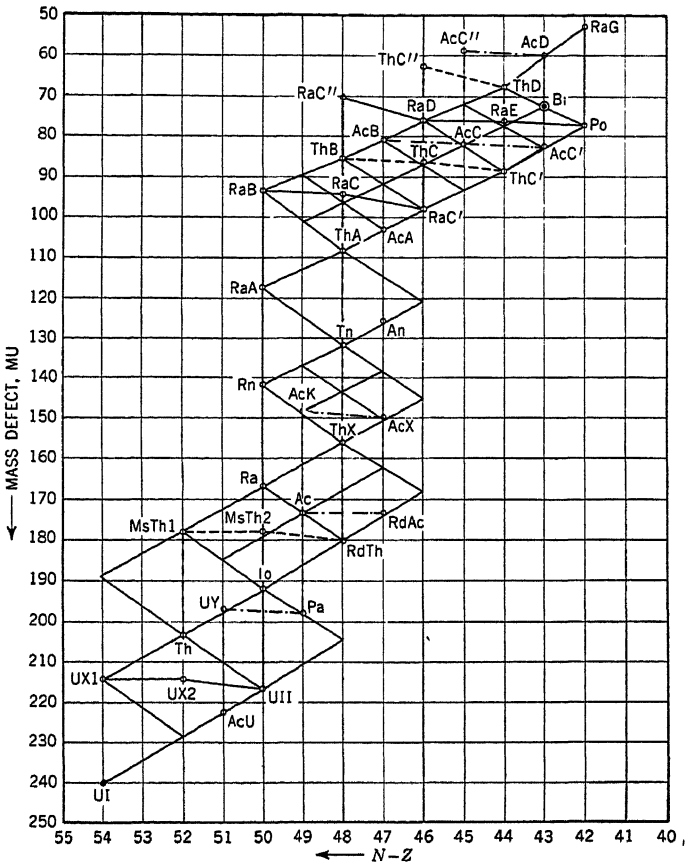


FIG. 21. The mass defects of the naturally radioactive elements: α-decay leads perpendicularly upward, β-disintegration two places to the right. Solid line, uranium-radium series; broken line, thorium series; dash-dot line, actinium series.

mined if the mass defect, say of uranium or thorium, is known. A single such constant is, however, sufficient for all three series, for, by using simple theoretical considerations, the relations of the three series to one another can be fixed. In all three series, for example, isotopes of thorium occur. These are: RdAc (227) in the Ac-series, RdTh (228) and Th (232) in the Th-series, Io (230) and UX 1 (234) in the U-series. The addition of neutrons to the lightest of these isotopes (RdAc) can be expected always to release about the same amount of binding energy, so that the mass defect increases approximately linearly with the mass within this series of isotopes. There should be a small difference with respect

to even and odd masses, such that the binding energy of odd mass (RdAc) is somewhat smaller than it would be according to the linear relation.*

Values obtained in this way have been included in the tables. Figure 21 illustrates this region of the heaviest nuclei: The mass defect is plotted in units of 10^{-3} MU, increasing from top to bottom. The neutron excess, $N - Z$, of the nuclei is a convenient variable and is plotted from right to left. The heavier lines represent the scheme of decay of the three families; the thinner lines correspond to the requirement, mentioned in the preceding paragraph, of linearity for isotopes (constant proton number) and "isotones" (constant neutron number).

27. α-Disintegration

The two characteristic quantities of an α-emitter are its decay constant, λ, and the energy of the emitted α-particles. As the residual nucleus experiences recoil in the process of emission, the energy of disintegration, Q, according to Equation (69) is somewhat larger than the kinetic energy of the α-particle. This quantity may appropriately be used in addition to the decay constant.

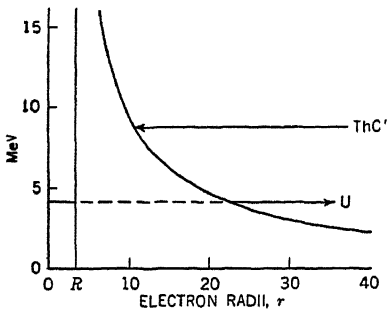


FIG. 22. Gamow's theory of α-decay.

The Gamow theory, which was mentioned on page 64 in connection with induced α-emission (though in very small time intervals), was developed originally for the problem of radioactive α-decay. Consider the uranium nucleus. Uranium is known to emit α-particles of 4.1 MeV energy. If the much faster α-particles of ThC′, with an energy of 8.8 MeV, fall on uranium nuclei and are scattered by them, an angular distribution of the scattered particles can be observed, exactly equal to that expected in a Coulomb field as described by Rutherford's scattering formula. If, in Figure 22, the potential barrier is plotted in the neighborhood of the uranium nucleus, we must accept as experimentally proved that the Coulomb repulsion remains effective up to the short distances from the center of the nucleus to which the fast ThC′ α-particles can attain. How, then, can the much slower α-particles of the spontaneous uranium decay escape from the nucleus? According to the fundamental laws of classical mechanics, this is impossible; according to wave mechanics, the possibility of a "tunnel effect," as treated on page 64, still exists. Evidently, the emission probability is reduced by a Gamow factor.

Taking into account Equations (56) to (58) and the statements on page 65, we can, therefore, immediately write for the decay constant of an α-active atomic nucleus:

$$\lambda = \lambda_0 G = \lambda_0 \frac{\alpha}{e^{\alpha} - 1} \tag{70}$$

λ_0 may be expected to be of the order 10^{17} sec^{-1}. The value, λ_0, will, of course, be subject to individual fluctuations from nucleus to nucleus, although it will not vary by many powers

* The values within one family are known relatively to each other up to a few 10^{-4} MU; the three families can be determined relatively to each other with a precision of about 10^{-3} MU. The absolute values of the mass defects, which lie around $1800 \cdot 10^{-3}$ MU, are correct only to about $\pm 10^{-2}$ MU.

of ten.* The results are listed in the accompanying survey. The empirically determined decay constant of the particular α-emitter is given below λ. In order to calculate the Gamow factor, the decay energy, Q, the nuclear radius, R, and the charge, Z, of the product nucleus formed have to be known. The nuclear radius may be assumed to increase proportionally to the cube root of the mass number. Any wider departures from this law should be expressed in considerable irregularities of the mass defects. Figure 21 shows at a glance that such irregularities can occur at best in the C- and C′-elements. The assumption:

$$R = 1.6 \cdot 10^{-13} \sqrt[3]{A} \text{ cm} \tag{71}$$

agrees well with a formula derived later (see page 101) for moderately heavy nuclei. The constant has here been chosen somewhat larger‡; the value is certainly reasonable, although

SURVEY OF THE α-EMITTERS†

Disintegrating nucleus	Decay constant λ, sec^{-1}	Energy of disintegration Q, MeV	$-\log G$	λ_0 10^{17} sec^{-1}
UI	$4.81 \cdot 10^{-18}$	4.21	36.1	55
UII	$0.82 \cdot 10^{-13}$	4.79	31.7	42
Io	$2.6 \cdot 10^{-13}$	4.76	30.7	13
Ra	$1.39 \cdot 10^{-11}$	4.88	28.0	1.4
Rn	$2.10 \cdot 10^{-6}$	5.59	23.8	13
RaA	$3.78 \cdot 10^{-3}$	6.11	20.5	12
RaC	$2.34 \cdot 10^{-7}$	5.61	22.5	0.07
RaC′	$4.6 \cdot 10^{+3}$	7.83	14.7	23
Po	$0.57 \cdot 10^{-7}$	5.40	24.0	0.6
Th	$1.3 \cdot 10^{-18}$	4.28	34.5	0.4
RdTh	$1.16 \cdot 10^{-8}$	5.52	25.9	9
ThX	$2.20 \cdot 10^{-6}$	5.79	23.2	3.5
Tn	$1.27 \cdot 10^{-2}$	6.40	20.3	25
ThA	4.95	6.90	17.5	15
ThC	$4.3 \cdot 10^{-5}$	6.20	19.8	0.026
ThC′	$2.3 \cdot 10^{+6}$	8.95	11.9	16
AcU	$3.08 \cdot 10^{-17}$	4.59	33.2	0.5
Pa	$6.86 \cdot 10^{-13}$	5.14	28.9	0.5
Ac	$1.6 \cdot 10^{-11}$	5.1	27.8	1
RdAc	$4.24 \cdot 10^{-7}$	6.16	22.9	0.34
AcX	$7.06 \cdot 10^{-7}$	5.82	23.0	0.7
An	$1.77 \cdot 10^{-1}$	6.95	18.1	2.3
AcA	$3.47 \cdot 10^{+2}$	7.51	15.5	11
AcC	$1.54 \cdot 10^{-5}$	6.74	17.9	0.00012
AcC′	$1.4 \cdot 10^{+2}$	7.58	15.5	4.2
Sm	$1.6 \cdot 10^{-19}$	2.4	36.2	3

† The C-elements, and especially AcC, deviate from the regular values. This is not surprising because, in this region, also, the mass defects show strong irregularities. For samarium, the only α-emitter that does not belong to the very heaviest nuclei ($A = 148$), the range of the α-rays has been measured with considerable precision at (1.13 ± 0.02) cm. But the range–energy relation is not very accurately known for such short ranges. The value 2.4 MeV for the energy of disintegration is, therefore, also uncertain and, accordingly, the value of λ_0 calculated from it. The C-elements and Ac are also β-emitters. The listed decay constant has been calculated for α-emission only using the branching ratio, $\beta : \alpha$.

* The time $1/\lambda_0$, characteristic for the decay, apart from the Gamow barrier, must be equal to the time that has passed until the excess energy distributed fairly equally among all the constituents of an atomic nucleus has been concentrated on a particle at the surface. As the kinetics of such a process are difficult to comprehend, even a rough theoretical estimate of this time is lacking. Only one point seems to be clear: this time has to be considerably longer than the time needed for an α-particle to cross the atomic nucleus and emerge at the surface, without requiring it to produce an energy concentration on the surface. This is about 10^{-20} sec.

‡ Because of the Coulomb forces and the somewhat different meaning here of the quantity, R, compared to page 101.

the extent of the increase is difficult to estimate. The logarithms of the Gamow factors, calculated in this way, are included in the accompanying table. Apparently, they are of a considerably different order of magnitude than the values discussed on page 66. The last column shows the values of $\lambda_0 = \lambda/G$. They lie between the limits $3 \cdot 10^{16}$ sec^{-1} < $\lambda_0 < 5 \cdot 10^{18}$ sec^{-1}; hence, they are spread out over more than two powers of ten. If 1.5 instead of 1.6 had been used for the constant in Equation (71), all values of λ_0 would be increased approximately by the factor 10. The width of the scattering region would not be changed.

Since, for the natural α-emitters, Z and R vary only within narrow limits, the particular value of the variable, α, is essentially determined by the decay energy. We can, therefore, consider Equation (70) as a correlation between the decay energy and the decay constant, with the latter varying by many powers of ten, due to the effect of the exponential function, whereas the decay energy varies hardly more than by the factor 2. Under the name of Geiger-Nuttall relation, this correlation was empirically known even before the Gamow theory; its explanation was the most severe test for the correctness of the Gamow theory.

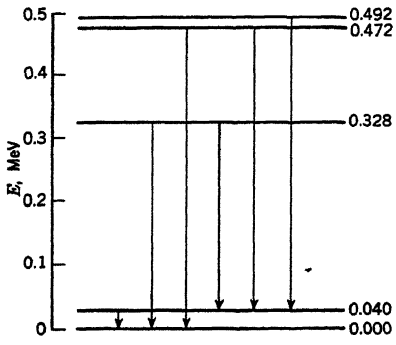


FIG. 23. Level scheme of the nucleus ThC″.

So far, only a homogeneous α-energy has been discussed, although on page 45 it was indicated that the energy of some α-emitters is not quite homogeneous, and that several range groups have been observed. The extensive experimental material concerning these energy groups has been obtained in investigations in which α-rays were deflected in magnetic and electric fields, mainly in the institutes of Cambridge (Rutherford, Briggs) and Paris (Rosenblum). The results show at least two characteristic phenomena:

1. Sometimes several range groups of comparable intensity occur. If, for example, ThC decays into ThC″, α-particles of the following energies are observed:

E_α, MeV	Intensity
6.084	27.2%
6.044	69.8%
5.762	1.80%
5.620	0.16%
5.601	1.10%

The explanation is obvious. If the ThC nucleus emits an α-particle of lower energy than the highest possible, the ThC″ nucleus is formed in an excited state. Consequently, the term scheme of the nucleus ThC″ can be constructed by means of the differences in the energies of disintegration (Q, not E_α). In this way, the levels represented in Figure 23 are obtained, between which the γ-transitions shown in the figure presumably ought to be possible and should occur following the α-disintegration. Actually, a number of γ-lines are observed with energies coinciding exactly with the differences shown in the figure. The transitions not shown in this scheme are not observed, hence they occur, if at all, only with very much less intensity. This absence of a number of lines indicates that in the atomic nucleus also, some kind of selection rules for radioactive transitions must exist, just as for the electron envelop of the atom.

2. For the very short-lived nuclei, ThC′ and RaC′, with half-life periods of approximately $3 \cdot 10^{-7}$ sec and $1.5 \cdot 10^{-4}$ sec, respectively, there occur, in addition to a main group

of α-rays, several groups of rays of longer than normal range, with intensities which are lower by 10^5 to 10^6 than that of the main group. If the main group corresponds to the transition from the ground state of the nucleus ThC′ to the ground state of the product nucleus ThD, then the groups of longer range have to be attributed to the transitions starting from an excited level of the nucleus ThC′. In contrast to the range groups treated under 1, the information obtained here concerns the level scheme of the initial nucleus and not that of the product nucleus.

The low intensity of these groups of unusually long range has to be interpreted in the following way: An excited ThC′-nucleus usually goes over into its ground state by a γ-transition. Only very rarely does it happen that the α-disintegration anticipates the λ-transition and that an α-ray of longer than normal range is emitted. That it happens at all is due to the rather short half-life period of the α-decay; therefore, the phenomenon is observed only for the extremely short-lived α-emitters, ThC′ and RaC′.

28. β-Disintegration

The number of radioactive elements emitting electrons has been considerably increased since the discovery of induced radioactivity in 1934 (Curie-Joliot). We know, today, not only the natural β-emitters in the region of the heaviest nuclei beyond lead, as well as the exceptionally striking natural β-emitters, ^{40}K, ^{87}Rb, and ^{176}Cp*, but also a great number of artificial β-active isotopes equally distributed over the whole of the periodic system. There is hardly an element without at least one β-active isotope. To these may be added a great many nuclei emitting positive electrons (positrons), especially among the lighter elements, for which the variety of possible nuclear reactions by means of which active nuclei can be artificially produced is very great.

All these β-emitters have one property in common: they emit not electrons of homogeneous energy, but a continuous spectrum of electron energies reaching from zero to an upper limit of, usually, about 1 to 2 MeV, though it can be smaller or larger. The nuclei with the most extreme values for the upper limit are probably $^{210}_{82}$RaD (0.026 MeV) and $^{12}_{5}$B (12 MeV).

The appearance of a continuum is very strange, indeed. If all initial nuclei of a radioactive substance have the same energy—and this has to be assumed, particularly if they are produced as a disintegration product of a homogeneous α-decay—and if different β-disintegration energies occur, then the product nuclei should have different energies at first, and a whole continuum of β-radiation should subsequently be radiated off, in order to bring all product nuclei into the same ground state. But this is not the case. In fact, numerous β-emitters emit γ-rays after the β-decay has taken place, but these always consist of a few sharp γ-lines of homogeneous energy and not of a γ-continuum. Furthermore, a considerable number of β-emitters have no accompanying γ-radiation, $^{210}_{83}$RaE being the most thoroughly investigated among them.

From the beginning it seemed possible to explain the strange contradiction by assuming that the observed β-continuum was only a simulation caused by secondary influences, such as slowing down of the original electrons and dissipation of their initial energy among secondary electrons, but that actually a sharp β-line existed primarily. Ellis and Wooster, in 1927, showed by a suitable experiment that this interpretation was not possible. They en-

* Cassiopeium = lutecium.

closed a known number, N, of RaE-atoms in a calorimeter during the time, t. In this time, $N(1 - e^{-\lambda t})$ atoms disintegrate. The same number of primary β-rays is, therefore, doubtlessly emitted. If all these rays have the homogeneous energy, E, the quantity of heat developed in the calorimeter during the time of observation should be:

$$Q = N(1 - e^{-\lambda t})E$$

This quantity of heat can be measured, and E can be calculated from it. In a primary line spectrum this energy, E, should coincide with the upper limit of the β-continuum. If, however, the continuum is of primary origin, E must equal the average β-energy of the continuum. The experiment was repeated under still better conditions by Meitner and Orthmann in 1930; the value obtained was $E = (0.337 \pm 0.020)$ MeV, whereas, according to the best measurements at that time by Flammersfeld, the upper energy limit of the β-continuum of RaE lay at $E_{max} = 1.170$ MeV, and its average energy at 0.331 MeV. The agreement between the calorimetric value and the average β-energy is excellent.

This proves conclusively that the observed β-spectra are primary continua. The validity of the law of conservation of energy seems at first to be impaired here. We can see at once that the law of conservation of angular momentum also is violated in the case of β-decay. Experimental evidence shows that atomic nuclei of even mass number have an integral nuclear spin, and those of odd mass number a half-integral spin (see Table I). Inasmuch as the mass number remains unchanged in a β-decay, the angular momentum should be able to change by an integer only (0, 1, 2, etc.), whereas the outgoing electron has the spin $^1/_2$ and withdraws from the system, so that the change ought to be half-integral.

Both difficulties are simultaneously solved if, as has been proposed by Pauli, the deficit in energy and angular momentum is attributed to a second particle which leaves the nucleus along with the electron in each β-decay, and which has such properties that it could hitherto elude detection by experiment. This particle is called *neutrino*. It must be uncharged, otherwise it would have been noticed long ago due to its ionization, and its mass can at most equal the electron mass, else it would have been noticed in a similar way as the neutron. In particular, it must not be absorbed to a noticeable extent by the walls of the calorimeter in the previously described experiment because it (the thickness) does not noticeably affect the energy balance of these measurements. The spin ascribed to it is $^1/_2\,\hbar$. If this is added to the spin of the electron, the difference in angular momenta becomes integral. The total energy of disintegration of the β-decay is to be equal to the energy of the upper limit of the continuum, plus the masses of electron and neutrino which are formed in this process. If an electron of kinetic energy, E_{max}, is emitted, only the kinetic energy zero remains for the neutrino. If the electron has a lower energy, the neutrino obtains correspondingly more energy, such that the sum of both energies is always equal to E_{max}.

An experimental proof for the identification of E_{max} with the disintegration energy can always be given where the energy difference of initial and final nucleus can be measured in some other way, independently of β-decay. The most obvious possibility is at the branching points of the radioactive series. Thus, the nucleus ThC either disintegrates first into ThC′ by β-decay, with $E_{max} = 2.25$ MeV, and subsequently into ThD by α-decay, with disintegration energy 8.95 MeV, or else it first goes over into ThC″ by α-decay, with 6.20 MeV, and subsequently into an excited nucleus ThD by β-decay, with energy of 1.79 MeV as the energy of the upper limit. In addition, Ellis could show that two γ-quanta with energies 0.58 MeV and 2.62 MeV are successively emitted. The balance is then as follows:

FIRST MODE OF DECAY		SECOND MODE OF DECAY	
ThC $\rightarrow$ C′:β	2.25 MeV	ThC $\rightarrow$ C″:α	6.20 MeV
ThC′ $\rightarrow$ D:α	8.95 MeV	ThC″ $\rightarrow$ D:β	1.79 MeV
		γ	2.62 MeV
		γ	0.58 MeV
Total:	11.20 MeV	Total:	11.19 MeV

Evidently the agreement is excellent. Similar, though not so accurate, comparative measurements exist for RaC and AcC and their subsequent branches. The recently discovered branching at Ac has not yet been investigated thoroughly enough to furnish another confirmation.

As the energy balance of the β-decay has to furnish not only the kinetic energy, but also the masses of electron and neutrino, the energy difference of initial and final nucleus is equal to the sum of the energy of the upper limit, electron mass, and neutrino mass. Use of this relation has been tried for an experimental determination of the neutrino mass. The precision of the numerical material at hand permits, however, only the statement that the mass of the neutrino is certainly not greater, and probably is smaller, than the electron mass.

Fermi, in 1934, attempted to form a quantitative theory of β-decay based on the idea of the neutrino. Evidently, a statement is required concerning the probability of the formation of an electron and a neutrino in the atomic nucleus and their subsequent emission. Since, according to our conception, which has hitherto been proved correct, the atomic nucleus consist only of neutrons and protons, Fermi makes the plausible assumption that both "light" particles, electron and neutrino, are created only at the moment of their emission by the transition of a "heavy" particle from the uncharged state (neutron) into the charged state (proton):

$$N \rightarrow P + e^- + \nu$$

In the case of positron emission, conversely:

$$P \rightarrow N + e^+ + \nu$$

This process is entirely analogous to the processes of emission of light in the electronic envelop. Here an electron goes over from a state of higher energy to one of lower energy, "creating" a light quantum, which also is emitted without having been a constituent of the electronic shell. An essential complication of Fermi's theory, as compared to the theory of the production of light quanta, consists in considering proton and neutron, so far regarded as two different particles, solely as two different species of the same type, i.e., of the "heavy" particles.

The creation of light quanta is governed by the Maxwell field between electrons. The creation of "light" particles in the nucleus is to be regulated in an analogous way by the field of the "heavy" particles, which we will call the Fermi field. In exactly the same way as the Maxwell field gives rise not only to the creation of light quanta, but also to the Coulomb repulsion between electrons, the Fermi field, in addition to the creation of light particles, has to give rise to the force acting between the heavy particles, i.e., to the forces keeping the atomic nuclei together. A most severe test of Fermi's theory is whether or not it succeeds in comprehending from a unified point of view the absolute size of these nuclear forces and the probability of the β-decay.

Fermi's original theory, though answering all these questions qualitatively, has failed almost completely quantitatively. The reason lies, of course, in our total ignorance of the

assumptions to be made for the Fermi field. The later forms of the theory differ, therefore, from the original only with respect to these assumptions. The form developed by Konopinski and Uhlenbeck is remarkable because the intensity distribution over the β-continuum predicted by them seem to agree perfectly with the observations. When, later on in the course of experimental investigation, departures were found in the neighborhood of the upper limit, they were at first believed to be experimental mistakes in this region of weak intensity. For some time it was customary to give as the correct values not the upper limits observed, but those extrapolated from the formula of Konopinski and Uhlenbeck (so-called K.U. values). But when the experimental investigation progressed further, it was shown that the departures from the K.U. theory were real, so that, today, the experimental upper limits are considered the most reliable.

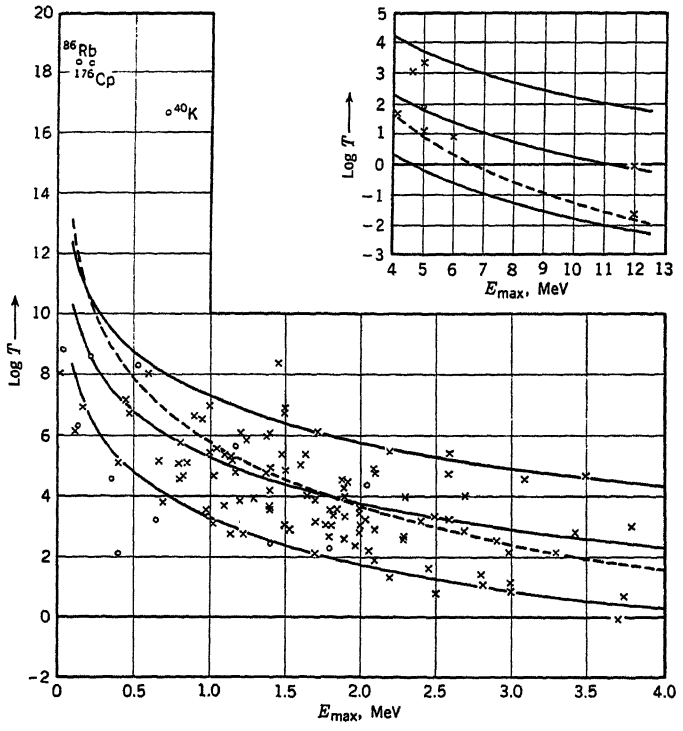


FIG. 24. Sargent diagram of β-decay: ×, induced β-emitters; ○, natural β-emitters. The solid curves correspond to the expectations of Fermi's theory ($\lambda \propto E_{max}^5$), the broken curve to the formula of Konopinski and Uhlenbeck ($\lambda \propto E_{max}^7$).

A further, qualitatively confirmed consequence of Fermi's theory, as well as of its K.U. extension, is the existence of a relation between the disintegration energy, E_{max}, and the disintegration probability. This was first found empirically by Sargent and represents an analogy to the Geiger-Nuttall relation in α-decay. In Figure 24 the values of $\log \lambda$ and E_{max} are plotted for numerous nuclei. The figure shows that the values are confined to a rather narrow region, and that the decay becomes more probable with increasing disintegration energy. The difference between the two forms of the theory are again considerable with respect to the quantitative statements: Whereas $\lambda \propto E_{max}^5$ was obtained for disintegration energies which are not too small ($E_{max} \gg 0.5$ MeV) in Fermi's original form, the K.U. theory requires a law of the form $\lambda \propto E_{max}^7$. The observed points scatter over such a large

region that it is hardly possible to decide between the two formulas. A theoretical explanation of the scattering may be based upon the fact that two more parameters, which are not the same for all nuclei, enter into the relation. (*a*) A matrix element containing the eigenfunctions of the heavy particles, thus taking into account the fact that the β-disintegration is not the conversion of a free neutron into a proton, but of a neutron bound in the nucleus into a bound proton. This matrix element, though always of the same order of magnitude, shows individual fluctuations from nucleus to nucleus. (*b*) A spin selection rule exists, according to which a transition involving a change of the nuclear spin by Δi is more improbable by a factor $(100)^{\Delta i}$ than a transition in which the spin remains the same.

The derivation of the force acting between the heavy particles of the Fermi field was first undertaken by Tamm and Iwanenko. The idea is approximately as follows: The interaction between proton and neutron is due to the virtual* disintegration of the proton into a neutron, a positron, and a neutrino, and the subsequent absorption by the neutron, after a very short time, of the two light particles thus formed. Thus, the scheme is:

$$P + N \rightarrow (N' + e^+ + \nu) + N \rightarrow N' + (e^+ + \nu + N) \rightarrow N' + P'$$

The corresponding process can likewise occur:

$$P + N \rightarrow P + (e^- + \nu + P') \rightarrow (P + e^- + \nu) + P' \rightarrow N' + P'$$

This shows that proton and neutron interchange their positions in the process. The action of a force connected with such an exchange of the two light particles is called *exchange force.* It is seen immediately that two different types of exchange forces can exist. As the particles have not only a charge which travels from one to the other, but a spin as well, we can distinguish between the two possibilities, that the spin is fixed either to the position or to the charge. This expresses itself in a spin dependency of the nuclear forces only in the case of antiparallel spins. The first type is called Heisenberg force, the second type, Majorana force.

This scheme fails as soon as the interaction between two protons is considered. As only the existence of the two reactions, $P \rightleftarrows N + e^+ + \nu$ and $N \rightleftarrows P + e^- + \nu$, follows from the β-disintegration, altogether four light particles are needed to be exchanged between the two heavy nuclei, corresponding to the following scheme:

$$P_1 + P_2 \rightarrow (N_1 + e_1^+ + \nu_1) + (N_2 + e_2^+ + \nu_2) \rightarrow (N_1 + e^+ + \nu_2) + (N_2 + e_2^+ + \nu_1) \rightarrow P_1' + P$$

An exchange of four particles is much more improbable than an exchange of two, hence the force between particles of the same type should be of a smaller order of magnitude than that between different types. Experiment has refuted this conclusion. From the experiments of Tuve, Heydenburg, and Hafstad on the scattering of protons by protons, a force is known to act between these particles apart from the Coulomb repulsion; the force is not only of the same order of magnitude as that between proton and neutron, but is even practically identical with it.

* A virtual intermediate state is one which exists for only a very short time. Due to the Heisenberg uncertainty relation, $\Delta E \cdot \Delta t \geqq \hbar$, an accurate definition of the energy of the state is impossible. Therefore, it does not have to satisfy the law of conservation of energy. The conservation of energy has to hold, however, for the final state into which the system goes over after the time Δt. Examples of such virtual states are quite frequent in quantum mechanics. In the Raman effect the absorption of the incident light quantum leads to such a state. It is, indeed, not compatible with the energy law because the energy of the primary light does not fit into the level scheme of the molecule. Another example is the compound nucleus in nuclear reactions, treated on page 64. Compare also the virtual production of the Yukawa particles in the nucleus, pages 88 et seq.

An extension of the original Fermi theory is, therefore, necessary. If the elementary processes, $P \rightleftarrows P' + e^+ + e^-$ and $P \rightleftarrows P' + \nu_1 + \nu_2$, are also allowed, and correspondingly for the neutron, $N \rightleftarrows N' + e^+ + e^-$ and $N \rightleftarrows N' + \nu_1 + \nu_2$, then the force between two heavy particles of the same type can also be explained by the exchange of only two light particles, e.g.:

$$P_1' + P_2 \rightarrow (P_1' + e^+ + e^-) + P_2 \rightarrow P_1' + (e^+ + e^- + P_2) \rightarrow P_1' + P_2'$$

To be sure, other processes besides β-disintegration should be possible, namely, those in which an electron–positron pair or two neutrinos are emitted. As the nucleus formed in these processes could also be reached by a γ-transition, and as the probability for γ-emission is so much greater than for β-decay and similar actions, the fact that such processes are never observed need not present any great difficulty. Therefore, attempts have been made to extend the Fermi theory in this way (Kemmer, Heitler).

Another approach to the problems was presented in 1935 by Yukawa who changed the fundamentals of Fermi's theory much more decisively. Yukawa visualized the process of β-emission as divided into two steps. First, a single charged particle (Y^+ or Y^-) is produced, which exists only virtually; hence, it disintegrates after a short time into a positive or negative electron and a neutrino:

$$P \rightarrow N + Y^+; \quad Y^+ \rightarrow e^+ + \nu$$

$$N \rightarrow P + Y^-; \quad Y^- \rightarrow e^- + \nu$$

The force acting between proton and neutron corresponds, then, to the scheme:

$$P + N \rightarrow (N' + Y^+) + N \rightarrow N' + (Y^+ + N) \rightarrow N' + P'$$

or else to:

$$P + N \rightarrow P + (Y^- + P') \rightarrow (P + Y^-) + P' \rightarrow N' + P'$$

Thus, the virtual Y-particle is again absorbed, unless it is energetically possible for it to disintegrate further. In order to include the force acting between proton and proton by the exchange of only one particle, a third uncharged particle, Y^0, must be introduced:

$$P_1 + P_2 \rightarrow (P' + Y^0) + P_2 \rightarrow P_1' + (Y^0 + P_2) \rightarrow P_1' + P_2'$$

This particle, the *neutretto*, could disintegrate into a positive and a negative electron, analogously to β-decay, but, again, this disintegration is not observed because of the preponderance of the disintegration of the neutretto into photons.

The advantage of the Yukawa conception, compared to Fermi's original one, was at first purely theoretical: The process of production and exchange of only a single particle shows a much stronger analogy to electrodynamics. The interaction between two electrons in the Maxwell theory can also be understood as follows: One electron produces a light quantum virtually, which is absorbed by the other electron:

$$e_1 + e_2 \rightarrow (e_1' + h\nu) + e_2 \rightarrow e_1' + (h\nu + e_2) \rightarrow e_1' + e_2'$$

Yukawa made further use of this analogy, even quantitatively. For light quanta, for example, the well-known wave equation holds:

$$\Delta\varphi - \frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2} = 0$$

For the Y-particle, a wave equation which differs from this only by a mass term should apply. Such a wave equation is well known from the De Broglie theory of matter waves. For a particle of mass μ:

$$\Delta\varphi - \left(\frac{\mu c}{\hbar}\right)^2 \varphi - \frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2} = 0$$

μ is now the mass of the Y-particle. In the Maxwell theory, electrostatics is obtained from the wave equation by removing the term containing the derivative with respect to the time. For the potential energy of the force acting between two electrons, the differential equation:

$$\Delta\varphi = 0$$

is then obtained, with the solution:

$$\varphi = \frac{e^2}{\hbar c}\frac{\hbar c}{r}$$

where the integration constant, e^2, has been arbitrarily expanded by $\hbar c$. The Yukawa theory gives analogously:

$$\Delta\varphi - \left(\frac{\mu c}{\hbar}\right)^2 \varphi = 0$$

with the solution:

$$\varphi = \frac{g^2}{\hbar c}\frac{\hbar c}{r}\, e^{-(\mu c/\hbar)r} \tag{72}$$

This should be the potential energy of the force acting between two heavy particles in the nucleus.* By experiment, this force is known to decrease approximately exponentially, in distances of the order of magnitude of the electron radius, $e^2/mc^2 = 2.81 \cdot 10^{-13}$ cm. Hence, the equation:

$$\frac{\hbar}{\mu c} \approx \frac{e^2}{mc^2}$$

has to hold approximately, or:

$$\frac{\mu}{m} \approx \frac{\hbar c}{e^2} = 137 \tag{73}$$

The Y-particle must, therefore, have a mass approximately 137 times that of the electron. Yukawa's theory has gained considerable probability since such particles have been observed in cosmic rays. They are called *mesotrons* or *mesons*. According to rather uncertain data, their mass lies between 50 and 200 electron masses. Whether they all have the same mass, or whether different masses occur, is not known. They are, in any case, of the right order of magnitude. Furthermore, from the experimental evidence concerning cosmic rays, they are known to disintegrate spontaneously in about 10^{-6} sec.

* The spin dependence of the nuclear forces does not find any expression here. This is due to the fact that we have confined ourselves to describing the light wave by a single scalar wave equation. Actually, a vector theory has to be constructed in order to take into account the transversal character of the light waves. The analogous method leads, for the Y-particle, to a vector theory in which the spin assumes the role of transversality. This idea, free of quantum-theoretical details, has been presented very clearly by H. Jensen, *Verhandl. deut. physik. Ges.* [3], **20**, 113 (1939). The spin dependence is of a different type than in the original Fermi theory. It contains a spin-orbit interaction which explains, for example, the observation that the deuteron has a small quadrupole moment.

The absolute magnitude of the nuclear forces obviously determines the value of the integration constant, g^2, in exactly the same way as the absolute magnitude of the Coulomb force determines the integration constant, e^2. In contrast to the very small value, $e^2/\hbar c = 1/137$, for the nuclear forces, a much higher value of about $g^2/\hbar c \approx 1/3$ is obtained.

The probability of the β-disintegration is not governed by this constant. This is an essential difference between the original Fermi theory and its transformation by Yukawa. The β-disintegration is divided into two steps: The first is characterized by the constant, g, and deals with the interaction of the Y-particle with the heavy particles; it allows the determination of g from the magnitude of the empirical forces between the heavy particles. The second step is concerned with the disintegration of the Y-particle into two light particles, thus dealing only with the interaction—described by another constant, g'—of the light particles with the Y-particle. With the help of these constants, two different experimental phenomena have to be explained: the order of magnitude of the β-lifetimes of atomic nuclei, and the lifetime of the spontaneous disintegration of the free mesotron. As $\hbar/\mu c^2$ is the only quantity with the dimension of time which can be formed from the elementary constants characteristic for the Y-particle, the decay constant for the spontaneous disintegration has to be:

$$\lambda = \frac{g'^2}{\hbar c}\frac{\mu c^2}{\hbar}$$

As λ is empirically of the order 10^6 sec^{-1}, the result is $g'^2/\hbar c = 10^{-17}$. The smallness of this value is responsible for the long lifetimes of the normal β-decay of atomic nuclei, although, quantitatively, the lifetimes would be more compatible with $\lambda = 10^8$ sec^{-1}.*

Another conclusion following from the theory of β-disintegration—quite similarly, in fact, for Fermi as well as for Yukawa—concerns the magnetic moment of proton and neutron. We have previously mentioned (page 19) that the magnetic moment of the proton, according to the Dirac theory, should be 1 NM, whereas the experimental value is 2.78 NM. Similarly, the moment of the neutron is -1.94 NM, although by Dirac's theory it should be zero. Both forms of the theory of β-disintegration, however, show that the originally sharply defined concept, "elementary particle," is somewhat unprecise because temporarily the neutron, for example, is dissolved into a proton and a Y^--particle. In this dissolved state, which lasts for a fraction $g^2/\hbar c$ of time, its magnetic moment will essentially come from the Y-particle; hence, it will equal approximately $e\hbar/2\mu c = M/\mu$ NM. In the time average, this gives for the magnetic moment of the neutron:

$$|\mu_n| = \frac{g^2}{\hbar c}\frac{e\hbar}{2\mu c} \quad \text{or} \quad |\mu_n| = \frac{g^2}{\hbar c}\frac{M}{\mu}\ \text{NM}$$

This should be equal to the empirical value, 1.94 NM. If $M/\mu \approx 1840/137$, $g^2/\hbar c \approx 1/7$ is obtained; this is, indeed, a plausible value, which is compatible with the absolute magnitude of the nuclear forces. The magnetic moment of the proton is produced by superimposing such a moment in the dissolved state upon the moment 1 NM in the undissolved state. Hence, it should be 2.94 NM instead of 2.78 NM. The small difference may be due to the fact that, owing to the spin dependence of the nuclear forces, the moments of proton and neutron may not be exactly additive in the deuteron. This effect is indicated also by the existence of a small quadrupole moment in the deuteron.

* A thorough treatment of all the fundamental questions connected with the meson and quantitative conclusions may be found in two papers of H. A. Bethe, *Phys. Rev.*, **57**, 260, 390 (1940).

29. K-Capture

Consider two isobaric atomic nuclei (nuclei with equal mass numbers), whose charges differ by one unit. At first glance, one of the two nuclei should be expected to be unstable and to be transformed into the other one, either by positron or by electron emission, depending on whether the heavier unstable nucleus has a Z greater or smaller than the lighter stable one. This expectation does not hold entirely, because in β-disintegration the masses of electron and neutrino have also to be furnished out of the mass of the original nucleus. A β-disintegration presupposes, therefore, that the heavy nucleus is heavier than the lighter stable nucleus at least by the sum of electron and neutrino masses.

Therefore, it would seem, at first, that an intermediate region of at least 10^{-3} MU width remains, within which two neighboring isobars could be stable simultaneously. A more detailed investigation has shown, however, that even in this region a process is possible which transforms the heavier nucleus into the lighter one.

Let $Z + 1$ be the charge of a nucleus. We shall bombard this nucleus by electrons. It may happen, then, that the nucleus captures an electron owing to the interaction, according to page 87, between light and heavy particles, and thus goes over into an isobaric nucleus of charge, Z. The nucleus thus formed can be only a virtual compound nucleus, for reasons of conservation of momentum; it goes over into the final nucleus by emitting either a γ-ray or a neutrino. Hence, the following reaction should take place:

$$_{Z+1}^{A}\text{nucleus}\ (e^-,\ \nu)\,_{Z}^{A}\text{nucleus}$$

Reactions which are induced by electrons hitherto have hardly been known. Only one case has been detected with certainty: Electrons of more than 1.6 MeV energy can excite the nucleus ^{9}Be to such an extent that it emits a neutron. The electron, in this case, is only inelastically scattered without being captured. Such a process may be expected to be considerably more probable than the reaction described above, in the proper sense. However, the cross section is only 10^{-31} cm^2.

If, therefore, the reproduction of nuclear transmutations by electrons seems to be hopeless, the situation becomes different if we consider that each atomic nucleus is permanently surrounded by the electrons of its shell. Two K-electrons are continually in closest proximity to the nucleus. Hence, if we are not interested in imparting kinetic energy to the nucleus, the nucleus need not be bombarded by electrons. An exothermic reaction which can be induced by electrons—as the foregoing reaction in positron-emitters—should, therefore, always be possible by capture of a K-electron.

This is not the case with the endothermic reaction in beryllium, mentioned previously, because the K-electron not only is unaccompanied by any positive kinetic energy, but has even a negative energy, the binding energy, $-E_K$, of the K-shell. If this were not so, the capture probability could not be calculated from the effective cross section, σ, by the simple formula:

$$w = \sigma v/V$$

where V is the volume in which the electron is enclosed, i.e., the volume of the K-shell (10^{-25} cm^3), and v its velocity ($v = 10^9$ cm/sec). The capture probability could then be obtained from $\sigma = 10^{-31}$ cm^2 as $w = 10^{-31}\cdot 10^9/10^{-25} = 10^3$ sec^{-1}. This would be a transmutation taking place after one thousandth of a second! In fact, however, those reactions in which an electron is actually taken into the nuclear system by transformation of a proton into a

neutron, and emission of a neutrino are doubtlessly much more improbable. They are actually observed in many cases with half-lives of the same order of magnitude as occur in β-emission.

This, then, is the picture obtained for neighboring isobars: The nucleus of mass M_1 and charge $(Z - 1)$ can emit a positron and go over into the nucleus of mass M_1 and charge Z, if:

$$M_1 \geqq M_2 + m_e + m_\nu$$

The nucleus of mass M_1 can also capture a K-electron of its own shell, emitting at the same time a neutrino, if:

$$M_1 - E_K/c^2 + m_e \geqq M_2 + m_\nu$$

hence, if:

$$M_1 \geqq M_2 - m_e + m_\nu + E_K/c^2$$

If an electron of the L-shell is to be captured, E_K must correspondingly be replaced by E_L. The probability for this process is, however, considerably smaller because the L-electron does not approach the nucleus so closely. Finally, the reverse process may occur; if the mass of the nucleus, M_2, is sufficient, it will emit a negative electron. Then:

$$M_2 \geqq M_1 + m_e + m_\nu, \quad \text{i.e.,} \quad M_1 \leqq M_2 - m_e - m_\nu$$

must hold.

The capture of a K-electron has a probability of the same order of magnitude as that for β-disintegration, provided that the disintegration energy is sufficiently large. If the disintegration energy is smaller, the K-capture has a greater probability. If we pass the limit below which positron emission is forbidden, K-capture remains the only possibility.

It may, therefore, be assumed that most of the positron-emitters disintegrated also by K-capture. However, this capture is very difficult to notice because it is almost unobservable. One might most likely succeed by observing a known number, N, of radioactive atoms of the decay constant, λ, during a time, t. During this time presumably $N(1 - e^{-\lambda t})$ atoms disintegrate. If this number coincides with the number of positrons emitted during the same time, the emitter in question is a pure positron-emitter. If, however, it is larger, part of the nuclei must have disintegrated by K-capture. The experiment has not yet been carried out; the essential difficulty is the determination of the number, N.

The direct observation of K-capture is not possible. It can be recognized only by the subsequent phenomena. These can be of two kinds: In some cases (often, but not always), a γ-ray is produced, just as in β-disintegration. This γ-ray is often transformed into an electron line. It releases an electron by photoelectric effect in the K- or L-shell of its own atom, in which it originated. Thus, for example, two electron lines are formed at 90 keV and 99 keV in the well-investigated ^{67}Ga, which must come from the internal conversion of a γ-ray of 100 keV.

Much more characteristic for K-capture are the x-rays to which it gives rise. A vacancy is produced by the disappearance of the K-electron in the lowest electronic shell, which has to be filled by electrons dropping from the higher shells. Hence, all the phenomena of the characteristic x-ray spectrum appear: The K_α-line (transition from L to K) in highest intensity, the K_β-line (transition from M to K) in lower intensity, and possibly even Auger electrons, which are released secondarily by x-rays.

The wavelength of these x-rays can be measured fairly accurately by a method proposed by Alvarez, which was first tried in the case of ^{67}Ga. The x-rays are obviously asso-

ciated with the disintegration product formed (in this case, ^{67}Zn). The K_α-line of Zn lies at 1.432A, the K_β-line at 1.293A. The absorption coefficients of the four elements, Ni, Cu, Zn, and Ga, are shown in Figure 25 for x-rays of different wavelength. Each spectrum has a break at the wavelength corresponding to the binding energy of the K-shell of the absorbing element, according to $h\nu = E_K$ ("K-edge"). X-rays of shorter wavelength can release photoelectrons from the K-shell of the absorbing elements and are, therefore, absorbed much more strongly than x-rays of longer wavelength, which can induce photoelectric effects only in the L- and higher shells. Below the four diagrams in Figure 25, the wavelengths of the characteristic lines of a few elements are indicated. Evidently, the K_α-line of zinc, comprising the major part of the radiation observed in this K-capture, has a discontinuity of the absorption coefficient between the elements nickel and copper. It is still strongly absorbed in nickel, but only weakly in copper. This expectation is fully confirmed by experiment. For the neighboring elements no break would occur at this place; for example, the K_α-line of gallium should be strongly absorbed in nickel and copper, but only weakly in zinc. Hence, in this case, it is certain that the observed x-rays belong to the product element, zinc.

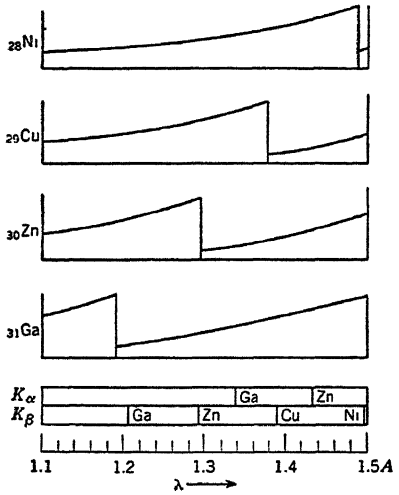


FIG. 25. X-ray absorption and emission spectra of four elements (schematic).

30. γ-Disintegration and the Problem of Isomerism

Hahn, in 1923, found that UX 1 not only goes over into UX 2 with a half-life period of 1.15 min, but that in part of the reactions it also disintegrates into another substance of half-life period 6.7 hr. As both substances are produced by β-radiation and, also by β-radiation disintegrate into the common final product UII, the same mass number, as well as charge, had to be assigned to UX 2 and to the 6.7 hr-body, which was named UZ. Both nuclei consist, therefore, of the same constituent particles and differ from each other presumably by a different arrangement of these constituents in the nucleus. Corresponding to the analogous phenomena in organic molecules, Hahn called two such nuclei *isomers*.

The discovery occurred at a time when ideas about the structure of atomic nuclei were still very obscure, and it remained isolated for a long time. Only much later, in 1937, did the real history of the problem of isomers begin. In activating bromine by capture of slow neutrons, three half-life periods of 18 min, 4.5 hr, and 34 hr were observed, the assignment of which created great difficulties because bromine consists of only two stable and approximately equally abundant isotopes of masses 79 and 81. By neutron capture, only the two isotopes 80 and 82 could be formed from them, and the question arose as to the origin of the third half-life. A way out was sought by assuming a third, very rare bromine isotope, but from the outset this assumption seemed very improbable. A clarification of the problem could be hoped for as soon as it became possible, through other nuclear reactions in bromine and its neighboring elements, to obtain more exact knowledge with respect to the assigning of these three half-life periods. The first decisive step was taken by Bothe and Gentner, who had discovered the nuclear photodissociation (γn), and hence were able to split off a

neutron from the stable bromine isotopes. The stable isotopes should thereby be reduced to the two isotopes 78 and 80. However, they found again three half-life periods instead of two—namely, one new period of 6 min and the two periods, already known, of 18 min and 4.5 hr. They drew from these observations the only possible conclusion that the half-life period of 34 hr, which occurs only in the capture process, has to be assigned to ^{82}Br; the 6 min one, which appears only in the splitting-off process, to ^{78}Br; and the two half-life periods of 18 min and 4.5 hr occurring in both processes, necessarily to ^{80}Br. The correctness of this method of assigning the half-lives has, in the meantime, been further confirmed by other authors, for example, with the help of the reaction $^{80}_{34}$Se $(p\ n)$ $^{80}_{35}$Br. The nucleus ^{80}Br exists, in any case, in two isomeric forms.

Since, under any circumstances, one of these two states must have the higher energy, the problem of isomerism is properly put in the following way: How does it happen that an excited nucleus does not go over into its ground state by γ-radiation, but is so long-lived that it is possible for it to undergo a β-disintegration, with a lifetime of many minutes or hours, anticipating the γ-transition? Or, in other words: How is it possible to understand the existence in an atomic nucleus of such highly forbidden γ-transitions that a metastable state is formed?

In order to understand this, let us estimate the transition probability between two levels in the nucleus. Normally, that is, in the case of dipole radiation, the γ-transition takes place in 10^{-14} sec. The selection rule in question requires a difference in angular momentum of the two levels of $\Delta i = 1$. If the difference in the angular momentum is greater, the transitions become progressively less probable, due to the appearance of increasing powers of the ratio, nuclear dimensions to wavelength. The half-life period of an excited level is generally given by the approximate formula:

$$\tau = 10^{-14}\left(\frac{\lambda}{2\pi R}\right)^{2(\Delta i-1)} \text{ sec} \tag{74}$$

If E is the energy difference of the two terms, $\lambda = c/\nu = hc/E$. The nuclear radii are of the order $8\cdot 10^{-13}$ cm for nuclei which are not too light. We obtain:

$$\frac{\lambda}{2\pi R} = \frac{\hbar c}{ER} = \frac{25}{E}$$

if E is measured in MeV. Hence, the order of magnitude of the half-life period is given by a relation of the following form:

$$\tau = 10^{-14}\ (25/E)^{2(\Delta i-1)} \tag{75}$$

Thus, we see: The greater the angular momentum difference, Δi, and the smaller the energy difference, E, of the two states, the longer the half-life period of the excited state. Some figures may illustrate this result:

$\Delta i =$	2	3	4	5	6	7
$E = 2.5$ MeV	$\tau = 10^{-12}$	10^{-10}	10^{-8}	10^{-6}	10^{-4}	10^{-2} sec
$E = 0.25$ MeV	$\tau = 10^{-10}$	10^{-6}	10^{-2}	10^{+2}	10^{+6}	10^{+10} sec

For an energy difference of a few hundred keV, which is quite likely in moderately heavy

nuclei, γ-half-life periods are obtained which are comparable to the half-life periods of β-disintegration, provided Δi has a value around 5.*

As the γ-transition is not entirely forbidden, one might expect to observe a weak γ-radiation besides the β-disintegration of the metastable state. The prospect is small because the probability for internal conversion of the γ-radiation (through photoelectric effect in the K-shell of its own atom) is very large, particularly for a small energy and a high difference in angular momenta. However, it should be possible to observe at least the conversion electrons formed in this process, and to infer from their energy the energy difference, E, between the metastable and the ground state. Pontecorvo (1938) was the first to succeed in this direction with the investigation of rhodium. Rhodium has an unstable isotope, ^{104}Rh, with two half-life periods, 44 sec and 4.2 min. A simple β-continuum belongs to the short period, and an electron line at about 60 keV is superimposed on the spectrum associated with the long period. If it is interpreted as due to electrons produced by internal conversion of γ-radiation in the K-shell, the original γ-energy has to be greater by the binding energy of the K-shell (25 keV). This leads to $E \approx 85$ keV in the case of rhodium.

The continuous β-spectra emitted by the two isomers coincide completely with each other as in the case of bromine. In fact, very nearly the same upper limit should be obtained for such a small energy difference of only 85 keV. But it is just as possible that both β-spectra originate in the short-lived ground state (44 sec), and that the occurrence of one of them with the half-life period of 4.2 min is only simulated by the fact that, due to their genetic connection, the two states reach a radioactive equilibrium after a period of time, and decay with the common half-life period of 4.2 min (see page 84).

In any case, the existence of conversion electrons assures a genetic relation between the two isomers. The existence of such a relation is not restricted entirely to rhodium. For example, it has also been detected for bromine, with an energy difference of 45 keV between the two levels. Thus, the following processes occur: The nucleus ^{79}Br captures a neutron, and the highly excited compound nucleus ^{80}Br is formed. It radiates away its excess energy during a very short time (10^{-14} sec) in several quantum jumps, because the γ-radiation which appears does not have the total energy of about 8 MeV, but, as it is much softer, is split into several quanta. At the end of these "cascades" some atomic nuclei reach the ground state, others the metastable state. The ground state disintegrates with the short period of 18 min. The long-lived metastable state, however, disintegrates with the long period of 4.5 hr, partly, perhaps, by β-disintegration into ^{80}Kr, certainly (at least partly) by emission of converted γ-radiation into the ground state. The 18 min-state is, therefore, continually formed by transitions from the metastable state. Whereas it was in excess at the beginning, because it was also formed primarily, it has disappeared as a primary product after some time has passed, and only the equilibrium amount, which has been supplied by transitions from the metastable state, is still in evidence. Hence, we observe, first, a decay of 18 min, then of 4.5 hr, both associated with β-radiation.

After the escape of the conversion electron the atom, lacking one K-electron, is in a highly excited state. After the vacancy is filled by emission of x-rays, an outer electron,

* The angular momentum argument presented here, essentially goes back to v. Weizsäcker. Instead of the angular momentum, any other symmetry property of atomic nuclei can be used for selection rules in a similar way, but the property of angular momentum is the simplest and the best known. Sachs recently tried to explain isomerism using another property [*Phys. Rev.*, **57**, 194 (1940)].

i.e., one of the electrons which cause chemical binding of atoms in the molecular structure, is missing. It can thus be expected that a molecule in which a nucleus has experienced an isomeric transition will, with a certain probability, later behave differently from the original molecules. This phenomenon may be used to carry out a separation of the two isomers by chemical means.

When this type of separation was first effected in Berkeley in 1939, it was thought that the separated atom was directly thrown from the molecular structure by the recoil caused by the emission of a K-electron. The guide here was an analogy to the Szilard and Chalmers (1934) process, in which radioactive atoms resulting from capture of a slow neutron become separated from their parent substance using the recoil energy which they obtain when the compound nucleus goes over into the ground state by γ-ray emission. From the momentum law, this γ-recoil energy, ϵ, is:

$$\epsilon = \frac{(h\nu)^2}{2\,Mc^2}$$

For a nucleus of medium mass ($M = 100\,M_{\mathrm{H}}$) and a normal γ-energy of 4 to 5 MeV, this leads to a recoil energy of $\epsilon \approx 100$ eV, an amount which is entirely sufficient to overcome the chemical binding energy. If, for example, an organic compound is used initially, the inactive atoms exist in a homopolar molecular system afterwards as well as before, whereas the active atoms are present in an ionized form in the solvent, and may be separated chemically from the inactive ones. The chemical procedure of isomer separation is rather similar, but it can easily be verified by calculation that the basic physical process is not recoil. For example, in ^{80}Br the recoil energy is:

$$\epsilon = (m/M)\cdot(E - |E_K|) \text{ for } E = 45 \text{ keV and } |E_K| = 13 \text{ keV, then } \epsilon = 0.22 \text{ eV only}$$

Although this is smaller than the binding energy of the C–Br-bond, the experiments of the Berkeley group were successful with *tert*-butyl bromide. On the other hand, separation was not obtained for ^{69}Zn because γ-rays, but not K-electrons, are emitted in its isomeric transition.

This separation experiment shows which of the two half-lives is to be assigned to the parent substance, and which to the daughter substance. At the moment of creation both are produced as primary constituents. If, for example, for bromine, the short-lived substance is metastable, it will have disappeared after about 2 hr, and only the long-lived daughter substance (the ground state) will remain. As only one such state exists, the separation can show only one half-life of 4.5 hr. The result is otherwise if the metastable state has the longer lifetime. Then, after 2 hr, the primary ground state will have disappeared and, instead of this, an equilibrium quantity of the ground state material, continually formed from metastable material, will be present. The 18 min-state can then be separated from the metastable 4.5 hr-state. The fraction which contains the ground state will then fall off in 18 min; the other fraction shows a decreased activity due to the equilibrium disturbance. An 18 min increase follows until the daughter substance is again built up, and the common decrease of the equilibrium mixture with 4.5 hr half-life period again takes place. This representation has also been verified in separation experiments with bromine, from which the genetic relation between the two isomeric states has been ascertained.

IV. SYSTEMATICS OF STABLE NUCLEI

31. Existence Rules

The existent stable nuclei fulfill a number of rules which may be stated as follows:

1. The Shell Rule. Because of their nuclear spin $^1/_2$, protons and neutrons form shells of two in the nuclei. If a neutron be added to a nucleus which possesses only closed shells, as, for example, a nucleus of even proton and neutron number (g–g type), this odd neutron is more weakly bound than the average of those in the shell. A second added neutron is, again, strongly bound. Nuclei with closed shells are, therefore, energetically more favorable, i.e., more strongly bound, than those corresponding to unclosed shells, such as nuclei with an odd neutron (Z even, N odd, g–u type), or an odd proton (Z odd, N even, u–g type), or an odd neutron and proton (Z odd, N odd, u–u type).

This fact has already been used in the construction of Figure 21 (page 79). This double periodicity is similarly marked if the mass defects of the lightest nuclei are plotted in the same manner against the neutron excess N–Z, as in Figure 26. Diagrams of this type are very useful in interpolating with some exactness mass defects of unknown nuclei.

2. The Isobar Rule. Two nuclei of the same mass number are called isobars. They can go over into each other by β-decay and K-capture (see page 91), changing their charge by ± 1 unit. The following three rules hold:

(a) No stable isobar pairs exist whose charges differ by only one unit (Mattauch).

Exceptions to this rule appear to be the isobar pairs Cd–In at mass number 113, In–Sn at 115, Sb–Te at 123, and Re–Os at 187. In these four cases the second named isotope is always relatively rare. The second isotope is supposed to be transformed in each of the four exceptions into the first by a very slow K-capture and, thus, is not stable.

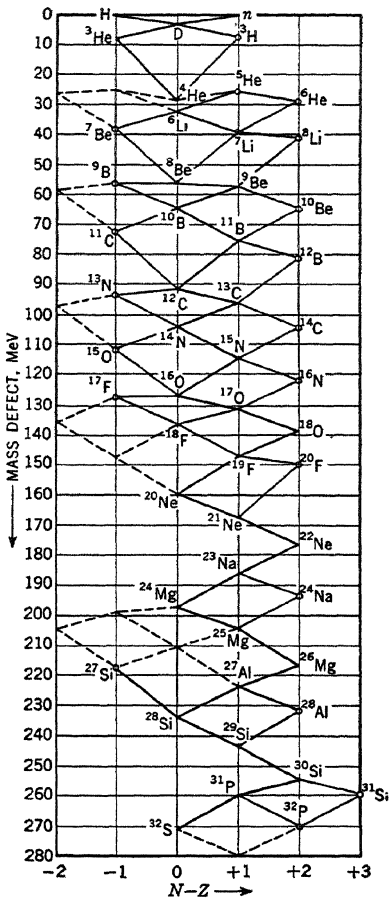


FIG. 26. The mass defects of the light atomic nuclei. Unstable nuclei are denoted by small circles. The straight lines connect the isotopic and isotonic nuclei.

(b) Nuclei of even mass number always have even Z and N (g–g type). Most of them have numerous isobars.

This rule, which simply maintains the nonexistence of stable nuclei of the u–u type, has four exceptions in the lightest nuclei, namely, the isotopes ${}^{2}_{1}D$, ${}^{6}_{3}Li$, ${}^{10}_{5}B$, and ${}^{14}_{7}N$. These deviations are explained by the fact that in the lightest nuclei strong individual fluctuations are still possible, as shown in Figure 26.

(c) Odd mass numbers do not possess isobars of odd charge number: Every odd mass number is represented by only a single stable nucleus of odd charge number.

This rule holds strictly and is without exceptions.

The three isobar rules can be understood more clearly by an examination of the energy surface. If the energy content of nuclei is plotted on an axis perpendicular to an N–Z plane, an "energy valley" is obtained along the narrow region of the N–Z plane occupied by stable nuclei. According to the shell rule, nuclei of the g–g type lie consistently deeper than the u–g and g–u nuclei, and these, in turn, lie deeper than the u–u nuclei. Therefore, strictly speaking, three energy surfaces rather than one must be constructed. Now, cut the energy surface with planes of constant mass number, A. In one case (Figure 27a), cut with an even mass number, in the other (Fig. 27b), with an odd. The first intersection plane contains nuclei of the g–g and u–u types, and gives two curves of approximately parabolic form. The second plane contains nuclei only of type g–u, which must lie on a single parabola-like curve. Figure 27a shows that every u–u nucleus is more unstable than both its neighbors of g–g type; the u–u nuclei can thus go over into one of the g–g type by β-decay or K-capture, so that they do not occur among the stable nuclei. On the other hand, the g–g nuclei would always have to jump two places at a time in a decay because the neighboring u–u place is energetically higher. As a double transition is impossible, stable nuclei exist far up on both the right and left sides of the g–g branch, so that nuclei of even mass number possess numerous isobars. The situation is considerably different in the case of odd mass numbers. Figure 27b shows that so long as a nucleus is not at the minimum of the parabola-like curve, it can reach there by steps of only one unit, i.e., by β-decay and K-capture. Thus, for each odd mass, only one nucleus exists—the one whose position is in the "channel" of the "energy valley."

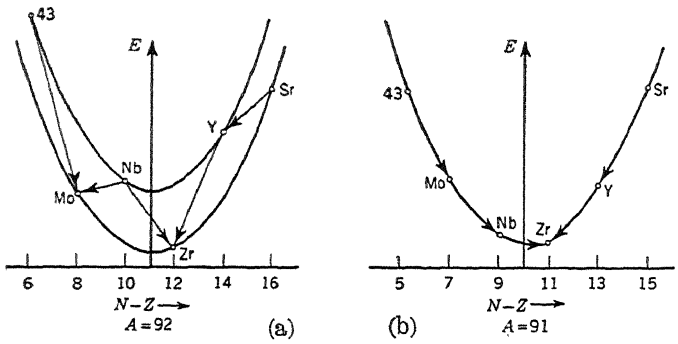


FIG. 27. Two intersections A = constant with the energy valley: (a) for an even mass number (two stable isobars, Mo and Zr); (b) for an odd mass number (one stable isobar, Zr).

3. Symmetry Rules. To a first approximation the structure of nuclei is symmetric in protons and neutrons.

Because of the Coulomb repulsion of protons, nuclei deviate from this rule more and more with increasing mass number. The deviation is in a direction of preference for neutrons in the system. Stable nuclei contain approximately equal numbers of protons and neutrons; their mass numbers are, therefore, approximately twice the charge number. This ratio increases from 2 to 2.6 with increasing mass.

Classification of nuclei according to the parameter Z (chemical classification; nuclei of equal Z are called *isotopes*) and classification according to the parameter N (nuclei of equal neutron number, N, are called *isotones*) should present broadly the same picture. The following comparison shows to what degree this is so:

(a) For stable nuclei Z goes from 1 to 83.

(b) For every odd Z only one or two isotopes exist and, if two, their mass numbers differ by two units. Their mass number is always odd (Aston).

Exceptions: The four light u–u nuclei ($Z = 1$, 3, 5, 7).

(c) For every even Z there exist at most one or two stable isotopes of odd mass number and, if two, they differ in mass number by two units.

Exceptions: $Z = 50$ (^{115}Sn, ^{117}Sn, and ^{119}Sn. The first is probably unstable with respect to K-capture).

(d) Almost all Z between 1 and 83 are occupied by at least one stable nucleus.

Exceptions: $Z = 43, 61$.

(e) Every nucleus of odd Z possesses an isotone with one proton less and also one with an additional proton.

There are no exceptions beyond oxygen.

(a) For stable nuclei N goes from 1 to 126.

(b) For every odd N only one isotone exists and, in rare cases, two, whose mass numbers differ by two units. Their mass number is always odd.

Exceptions: The four light u–u nuclei ($Z = 1$, 3, 5, 7).

Cases of two isotones: $N = 55$ (^{97}Mo and ^{99}Ru), $N = 85$ (^{145}Nd and ^{147}Sm), and $N = 65$ (^{115}Sn and ^{113}Cd. ^{115}Sn is probably unstable due to K-capture).

(c) For every even N there exists at most one stable isotone of odd mass number. In rare cases two exist, with mass numbers differing by two units.

Exceptions: None.

Cases of two isotones: $N = 20$ (^{37}Cl and ^{39}K), and $N = 82$ (^{139}La and ^{141}Pr).

(d) Almost all N between 1 and 126 are occupied by at least one stable nucleus.

Exceptions: $N = 19, 21, 35, 39, 45, 61, 89, 115$, and 123. The number of exceptions is strikingly high.

(e) Every nucleus of odd N possesses an isotope with one neutron less and also one with an additional neutron.

The rule holds beyond oxygen with the exception of $N = 85$ (^{146}Sm and ^{148}Sm corresponding to ^{147}Sm—the first not known, the second α-active), and $N = 87$ (^{148}Sm and ^{150}Sm corresponding to ^{149}Sm—the first α-active).

32. Binding Energy of Atomic Nuclei

The masses of nuclei lie very close to integers, even though the proton and neutron masses are about 0.8 to 0.9% larger than 1. From this, it follows that, to a first approximation, the binding energy increases proportionally to the number of particles in the nucleus, or that the average binding energy per particle in the nucleus is constant at about 8 MeV. As the binding energy is much more characteristic than the mass defect given in the tables, or the packing fraction, usually given in experimental results (see page 12), this binding energy per particle has been plotted in Figure 28 as a function of the mass number.

Why the binding energy per particle should be approximately constant is not obvious. This occurs whenever the forces act only between a particle and its nearest neighbors, i.e., when the range of the forces between the elementary constituents, neutron and proton, is much smaller than the diameter of the nucleus. This circumstance makes it possible to picture the nucleus, according to the following model:

Particles are packed densely in the nucleus in such a manner that each particle in the nuclear interior has twelve neighbors. Each particle can be bound to its neighbors by "valence bonds." The same amount, U_0, of the total binding energy corresponds to each bond because of the interaction of the two particles. For the sake of simplicity, the kinetic zero-point energy is also included in the quantity U_0. If each of the twelve valence bonds leaving a particle at each of its endpoints is counted as $^1/_2$, each particle in the nucleus contributes $-6\,U_0$ to the binding energy. In this approximation the total binding energy, $-6\,U_0A$, of a nucleus is proportional to the number of particles, A.

The foregoing representation requires correction. We must first take into account that this simple analysis does not hold for the surface of the nucleus. There, a perturbation of the kinetic zero-point energy proportional to the magnitude of the surface ($4\pi R^2$) takes place. Moreover, the potential energy must experience a correction which can be determined semiquantitatively. If a is the average distance of the particles in the nucleus, then in a surface layer of thickness a, i.e., in a volume $4\pi R^2 a$, there will be:

$$\frac{4\pi R^2 a}{\frac{4\pi}{3}R^3}A = 3\frac{a}{R}A$$

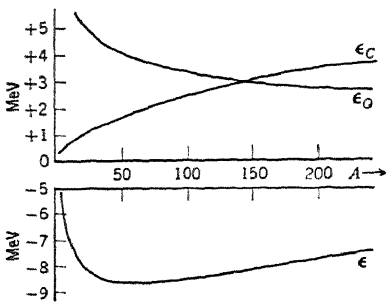


FIG. 28. The packing fraction curve (below), and its additive parts, Coulomb energy and surface energy (above).

particles. Six of the valence bonds of these particles are directed outward and cut through the surface, so that their contribution to the binding energy must be deducted. Since each enters into our calculations with a weight $^1/_2$, we have to subtract:

$$E_O = 3\frac{a}{R}A\frac{6}{2}U_0 = 9\frac{a}{R}AU_0$$

from the binding energy. We shall call E_O *surface energy* as it is calculated exactly analogously to the surface energy of a liquid drop. E_O is, in fact, proportional to the amount of surface because A is proportional to R^3.

Still to be considered is the *Coulomb repulsion* of the protons. The energy of a homogeneously charged sphere of radius R with total charge Ze is, according to classical electrostatics:

$$E_c = \frac{3}{5}\frac{Z^2e^2}{R}$$

In contrast to the main portion of the nuclear binding energy, the Coulomb energy is proportional to the square of the particle number, Z. This proportionality arises from the fact that the large range of the Coulomb force permits every particle to interact with every other.

Combining these three terms gives for the total binding energy of a nucleus:

$$E = -6\,U_0A + 9\frac{a}{R}U_0A + \frac{3}{5}\frac{Z^2e^2}{R}$$

or for the binding energy per particle:

$$\epsilon = \frac{E}{A} = -6\,U_0 + 9\frac{a}{R}U_0 + \frac{3}{5}\frac{Z^2e^2}{AR}$$

This formula gives us a qualitative understanding of the change of mass defects with mass number. If we put, as is approximately true, $R \sim A^{1/3}$ and $Z \sim A$, we obtain for ϵ an expression of the form:

$$\epsilon = -\epsilon_1 + \epsilon_2 \cdot A^{-1/3} + \epsilon_3 \cdot A^{2/3}$$

The surface force depresses the binding energy in light nuclei, but has little importance in heavy nuclei. For heavy nuclei the binding energy is depressed, i.e., a weakening of the nuclear structure takes place, due to the Coulomb repulsion of the protons, which is relatively unimportant in light nuclei. A glance at Figure 28 shows that these statements agree completely with experiment; nuclei with mass numbers between 50 and 80 are the most stable.

Our formula would be an adequate approximation if we did not have to consider that the nucleus is not completely symmetric in neutrons and protons, but that a neutron excess develops for heavy nuclei. As long as Coulomb energy is neglected, nuclei with $N = Z$ evidently possess the largest binding energy; nuclei with $N - Z \lessgtr 0$, for $N + Z = A =$ constant, must lie on parabola-like curves, as discussed on page 98 and illustrated in Figure 27. This means that our formula may be replaced by the somewhat more general one:

$$\epsilon = -6\,U_0\left[1 - \gamma\left(\frac{N-Z}{N+Z}\right)^2\right] + 9\,\frac{a}{R}\,U_0 + \frac{3}{5}\frac{Z^2e^2}{AR}$$

If, in addition, the approximation $R \propto A^{1/3}$ is used, a formula is obtained which, as a very good approximation, may be written:

$$\epsilon = -14.66\left[1 - 1.40\left(\frac{N-Z}{A}\right)^2\right] + 15.4\,A^{-1/3} + 0.602\,A^{-4/3}Z^2$$

ϵ is in MeV. This corresponds to the expression for the nuclear radius:

$$R = 1.42 \cdot 10^{-13} A^{1/3}\ \text{cm}$$

which is in very good agreement with the formula for the radii of the heaviest nuclei, derived on the basis of Gamow's theory of α-decay (see page 81).

The most stable nuclei, i.e., those Z which have a minimum of energy for fixed A (the "valley"), because of the Coulomb term will no longer lie at $N - Z = 0$ or $Z = A/2$, but are to be obtained from the condition:

$$\left(\frac{\partial \epsilon}{\partial Z}\right)_A = 0$$

This gives a numerical relation:

$$Z = \frac{A}{2 + 0.0146\,A^{2/3}}$$

The values for Z obtained from this formula are compared with the empirical Z-values in the accompanying table. The agreement is perfect. The table, in addition, contains the binding energy per particle split into the three constituent parts (volume energy, surface energy, Coulomb energy). The values are given in MeV and are calculated for those Z-values in bold type. The resulting curve is sketched in Figure 28.

A	Z (theoretical)	Z (empirical)	Parts of ε in MeV			ε MeV
			Volume energy	Surface energy	Coulomb energy	
20	9.5	10	−14.66	+5.67	+1.11	−7.88
40	18.4	18, 20	−14.46	+4.50	+1.43	−8.53
60	27.0	28	−14.56	+3.94	+2.02	−8.60
80	35.2	34, 36	−14.46	+3.58	+2.25	−8.63
100	43.1	42, 44	−14.36	+3.32	+2.52	−8.52
120	50.9	50, 52	−14.09	+3.12	+2.55	−8.42
140	58.4	58	−14.06	+2.97	+2.78	−8.31
160	65.8	64, 66	−14.02	+2.84	+3.02	−8.16
180	73.0	72, 74	−13.83	+2.72	+3.06	−8.05
200	80.0	80	−13.83	+2.63	+3.29	−7.91
220	86.9	(86)	−13.67	+2.55	+3.34	−7.78
240	93.6	(94??)	−13.68	+2.48	+3.57	−7.63

33. Abundance Rules

The abundances of the stable nuclei are conditioned by their historical origin. That is to say, this problem properly lies outside the realm of nuclear physics and belongs to cosmology and astrophysics. If the elements are assumed to have been formed at such a high temperature that thermal equilibrium could be established between the nuclei and their free constituents, the abundance of elements and isotopes might be expected to depend directly upon the binding energy, and the dependence should be such that the most abundant atomic nuclei are the most stable. Such a relationship is very clearly shown empirically. From a purely nuclear-physical standpoint, interest in the problem centers upon the possibility of obtaining more information about nuclear binding energies from the abundance. A more provocative problem, however, would be to draw valuable conclusions concerning the origin of the elements at a later time when the empirical material relating to binding energies and absolute abundances will be more complete.

If we attempt to derive these abundances from a thermodynamic equilibrium, it is clear that this equilibrium lies strongly on the side of nuclei which could show only a small dissociation into neutrons and protons. Therefore, the binding energy of the weakest neutron in the nucleus, not the average binding energy as obtained from the packing fraction curve, would be important. This difference has heretofore probably been heeded too little,* presumably because the absolute abundance of the elements, aside from strong individual fluctuations, decreases monotonously with increasing charge number, and shows no strong maximum in the mass region between 50 and 60 where the average binding, per particle, according to the packing fraction curve, possesses a maximum.

In any event, the following *main rule* may be stated: Nuclei of *g–g* type overbalance both in number and abundance those of *g–u* and *u–g* types, which are about equally abundant. Those of *u–u* type hardly ever occur.

This rule is a direct consequence of the shell rule (page 97). Of the 272 stable nuclei, 160 are of *g–g* type, 56 are of *g–u* type, 52 are of *u–g* type, and only the four extremely light nuclei, ^{2}D, ^{6}Li, ^{10}B, and ^{14}N, are of *u–u* type.

* In a recent paper Krishnan and co-workers report that they produced the reaction ^{63}Cu (d, 2 n + p) ^{62}Cu with a deuteron threshold energy of 7 MeV. This corresponds, if we take the deuteron binding energy to be about 2 MeV, to a binding energy of the weakest neutron in the ^{63}Cu-nucleus of about 5 MeV. On the other hand, according to the packing fraction curve, Cu falls in the region of strongest average binding energy of 8.63 MeV.

Elements with odd Z thus contain only isotopes of u–g type, whereas elements with even Z comprise, besides the g–u nuclei, the more abundant g–g nuclei. The following important rule may, therefore, be stated: The absolute abundance of elements with even Z is larger than that of elements with odd Z (Harkins). If the strong individual fluctuations from element to element are neglected, then quantitatively the odd elements, on the average, are one-tenth as rare as their even neighboring elements. The lightest elements occur most frequently on the earth as well as on the sun. The absolute abundance decreases from element to element, on the average, by the factor 1.2 to 1.3. It follows from this that the heaviest stable elements ($Z = 83$) are rarer than the lightest by the factor $(1.2)^{83} = 10^7$.

As an example of the strong individual fluctuations of the abundance, examine the inert gases. The absolute abundances of the inert gases decrease steadily from helium to neon, krypton, and xenon by about two powers of ten. Argon also would agree well with this rule if it had only the two isotopes, ^{36}A and ^{38}A. The main isotope, ^{40}A, is completely anomalous; its abundance is about 300 times too large. This phenomenon has nothing to do with the binding energies. Rather, it is to be attributed to the fact that ^{40}A was probably formed from the unstable isotope, ^{40}K, by K-capture. The natural β-activity of potassium causes the decay of ^{40}K to ^{40}Ca by electron emission. Thus, in the course of time, the abundance has increased enormously (v. Weizsäcker).

Thanks to mass spectrography, the relative abundances of the individual isotopes of the same element have become much better known than the absolute abundances. The two following rules may be mentioned particularly:

1. Inasmuch as series of many isotopes exist only for even charge numbers (e.g., in Cd or Sn), and as this is the case only because of the abundant nuclei of g–g type, these elements may be examined separately. If the abundances of the g–g nuclei of an element are plotted against their mass numbers, in general a type of bell curve is obtained, which has a maximum at a central mass number and falls off rather steadily towards left and right. This "bell curve," of course, is not everywhere symmetric, but often drops slowly at one side and steeply on the other, e.g., for barium, where the heaviest isotope is also the most frequent. However, two maxima never occur.

This rule is explained by the fact that such a series of isotopes represents an oblique cut through the energy valley, so that special binding strength is to be expected in the region of a central mass number; to the left and right of it, however, the abundances decrease with the weakened structures.

The only pronounced exception to this rule is samarium. The relative abundances actually are not known very exactly; nevertheless, a striking minimum exists in the center, but to the left and right large abundances are found:

Mass number	144	146	148	150	152	154
Relative abundances	3%	0%	14%	5%	26%	20%

Why this anomaly exists is not entirely clear. We know, however, that the regularity of the energy surface also is disturbed in samarium; isotope 148 is the only nucleus below polonium showing α-activity. Thus, its original abundance was certainly somewhat higher—at most, however, as a result of its very long life, by several per cent, even 10^{10} years ago. That isotope 146 does not occur indicates, perhaps, that it has died out, due to a short-life α-decay. Finally, one should recall the remarkable transition in nuclear structure

between isotopes 150 and 152, found by Schüler and Schmidt as a result of their observations in the samarium spectrum (see the conclusions on page 14).

2. If elements of odd charge number are examined, only one or two isotopes of *u–g* type are found with mass numbers differing by two units. Elements of even charge number are related in the same manner to isotopes with odd mass number, i.e., of the *g–u* type (see page 98). The rule may, therefore, be stated that the relative abundance of these two isotope types is approximately equal. If the four cases in which one isotope has an isotone for a neighbor, so that a secular *K*-capture may have displaced the abundance ratios, are disregarded, twenty-five cases remain in which the abundance ratio of the two isotopes has the following values: In thirteen cases the ratio is between 1.0 and 1.3, in eight further cases between 1.3 and 2.0, in only two cases between 2 and 3, and in only two cases beyond 3, namely chlorine (3.06) and potassium (14.3). The very extreme abundance ratio of ^{41}K and ^{39}K is, thus, the one very striking exception to this rule. It is well explained (as it is, also, for chlorine) by the fact that in light nuclei the one with the small neutron excess is markedly preferred energetically.

The four cases differentiated here, in which *K*-capture probably plays a part (page 97), are the following:

(a) $^{113}_{48}$Cd shows no abundance anomaly; $^{113}_{49}$In, however, does, but it is too rare. Perhaps ^{113}In is impoverished by *K*-capture, but ^{113}Cd can show no corresponding increase because the absolute abundance of ^{113}Cd is considerably greater than that of In.

(b) $^{115}_{49}$In can result from $^{115}_{50}$Sn. ^{115}Sn is very much impoverished. As tin is more abundant absolutely than indium, an excessive abundance should be observed for the resulting product, ^{115}In; this actually occurs, but it probably results partially from the impoverishment of ^{113}In, mentioned previously.

(c) $^{123}_{51}$Sb can result from $^{123}_{52}$Te. Here, the ^{123}Te is impoverished but the resulting product is not enriched because antimony is more abundant absolutely than tellurium.

(d) $^{187}_{75}$Re can result from $^{187}_{76}$Os. The isotope ^{187}Os is about ten times as rare as stable $^{189}_{76}$Os, so that an appreciable impoverishment must have taken place. The absolute abundance of osmium is about ten times as large as that of rhenium. A large enrichment of ^{187}Re should, therefore, be expected. Strangely, however, it is only 1.62 times as abundant as the other isotope, ^{185}Re. This appears to constitute a real exception to the rule.

The rule states that, in general, the "channel" of the energy valley (page 98) runs approximately between both isotopes for nuclei of *g–u* and *u–g* type.

NUCLEAR PHYSICS TABLES

BY J. MATTAUCH

EXPLANATION OF TABLES

The tables are so classified that the first group (Tables I–III) contains essentially the observed data on stable nuclei (Division I in the text), and the second group (Tables IV–VI) is devoted mainly to nuclear reactions and the unstable nuclei (Divisions II and III in the text). Because the two groups overlap only slightly, they have been provided with separate (alphabetically arranged) bibliographies. The references given in the tables refer to this list; the first letter refers to the experimenter, and the following numbers list the papers under that letter. As a rule, only the best values are given for the numerical figures; these have been obtained from the methods which seemed most reliable. Wherever possible, the error estimated by the experimenter is given. Throughout, parentheses signify uncertain entries.

Table I contains, aside from the neutron and the naturally occurring isotopes (those observable in a mass spectrograph), the β-stable, α-active elements of the disintegration series, as they are needed to determine the packing-fraction curve between lead and uranium. In addition, the β-active AcK and the dual-decaying Ac have been brought in as the only representatives of charge numbers 87 and 89.

The first rows contain the charge (proton) number, Z, the name of the element, the chemical symbol, the neutron number, N, and the mass number, A, of the isotope. The type of decay (β or α) is then given, also the value of the nuclear mechanical moment (spin, i, in units of $\hbar = h/2\pi$). The references in the annexed literature column relate to both of these. Several literature references are cited because the spin has been measured by several of the methods described in section Ie (page 18). After this come the columns for the nuclear magnetic moment, μ, in nuclear magnetons (1 NM $= \hbar e/2\, M_p c$), and the quadrupole moment, q (measured in 10^{-24} cm^2), both with the corresponding references to the literature. If the spin of a nucleus is not yet known, the nuclear g-factor, if it has been measured, is given in the column for μ. As $g = \mu/i$ (see page 37), the nuclear magnetic moment, μ, may be easily obtained if the spin is known.

The column for the relative abundance of the isotopes of an element contains the direct results of the cited observers, with the error (in per cent). Values occurring one underneath the other refer to numerical ratios, where the relative abundance of one isotope often has been set equal to 1 or 100. The ratios of the isotopes are not always the same for a given element; in that case, two sets of numbers are included in this column. The observations, also, frequently have been derived from different experimenters. (The per cent abundances calculated from these results may be found in Table IV, column 5).

EXAMPLES: Relative abundances of $^{32}S:^{33}S:^{34}S = 100:78 \pm 2\%:4.4 \pm 2\%$, and $^{32}S:^{36}S = 6000 \pm 10\%:1$ (observer N 8); or relative abundances of $^{182}W:^{183}W:^{184}W:^{186}W = 74.8:$

57.1 : 100 : 99 (observer A 8) and $^{180}W : ^{183}W = 0.01 : 1$ (observer D 5). Where this is explicitly denoted by the sign %, the results mean per cent of the total intensity of all isotopes.

The meaning of the other columns of Table I is obtained directly from the headings at the top of the table (and from the statements on pages 11 et seq. and 17 et seq.). All the observed material of Tables III and VI has been used for calculation of the isotopic weights (see Table IV, column 10), the packing fractions, f, and the mass defects.*

Table II contains the estimates made, up to the present time, on the maximum possible abundance (in per cent of the total intensity) of nonexistent isotopes, for it is often important, in interpreting and classifying nuclear reactions and artificially radioactive nuclei, to know with what certainty isotopes which probably do not occur in nature can be ruled out.

In *Table III* the mass-spectrographic material for calculation of isotopic weights is collected. In the first (untitled) column the isotopes whose masses were calculated using the doublets (or bracketing) are given. A should be interpreted as the "mass number" (not necessarily integral) at which the measurement was taken. The specification of the two lines forming the doublet follows; the line which corresponds to the heavier mass is always written first, so that the mass difference, $\Delta M = M_1 - M_2 = A(f_1 - f_2)$, of the next column is always positive. For higher mass numbers (generally less exact measurements), the table gives only the most directly measured quantity, $\Delta M/A$, equal to the difference of the packing fractions, $f_1 - f_2$, of the two lines forming the doublet.

For the heavy elements, so-called brackets must be used frequently. The line for the isotope of an element is bound on both sides by the lines of two isotopes of another element. (In rare cases the first line lies outside the bracket.) The "center" of the bracket then forms a "doublet" with the bracketed line whose mass number is given under A. As the bracketed line is always written first in the column entitled "bracketing," the packing-fraction difference which follows, $\Delta M/A = f_1 - \bar{f}_2$, can be positive or negative. Actually, $\bar{f}_2$ should have been taken as the arithmetic mean of the packing fractions, f_2' and f_2'', of the bracketing lines only if the "mass number" of the bracketed line lies in the center of the "mass numbers" of the two bracketing lines. In general, $\bar{f}_2 = {}^1/_2(f_2' + f_2'')$, $\bar{f}_2 = {}^1/_3(2f_2' + f_2'')$, $\bar{f}_2 = {}^1/_4(3f_2' + f_2''), \ldots$, according as the mass number of the first line divides the difference of the two others in the ratio 1:2, 1:3, 1:4. At any rate, if the arithmetic mean for $\bar{f}_2$ is always used, the error will never be greater than the error of observation.

Table IV contains the stable and unstable nuclei, so far as they are now known, together with their most important properties and the nuclear reactions carried out among them. One row is devoted to every type of atom and, for convenience, the specification of the nucleus in the ordinary way (chemical symbol with mass number as upper left index) is repeated on the right border of the table. Using this notation together with the column numbers (red number in square brackets), the references for every entry in the tables can be found in the footnotes.

The chemical symbols which may be used for all isotopes of an element, and which are consistently labeled with A and Z as indices, are given in column 2 in **bold** print. The special symbols of individual nuclei appear in ordinary print. Ordinary print for the chemical symbol at the beginning of a new page denotes the continuation of an isotope series started on the previous page. In columns 3 and 4, the neutron number, N, and mass number, A, of the stable nuclei are printed in **bold** print, of the naturally radioactive nuclei in

* For details of this calculation, see S. Flügge and J. Mattauch, *Physik. Z.*, **42**, 1 (1941).

italics, and of the artificially produced nuclei in ordinary print. Isomerism with the preceding nucleus is denoted by "isomer" and is also given in the literature section. In the specification on the right border of the table, the two isomeric states are distinguished by an asterisk, e.g., ^{80}Br and ^{80}Br*. The excited state is obtained, in the better known occurrences, from the data on β- and γ-radiation from column 12. If the assignment of activity to a given mass number is uncertain, the mass number and the neutron number are put in parentheses. Similarly, the entry "(isomer)" means that the isomerism is questionable. Frequently, the assignment may be possible or probable only to two mass numbers. In this case the two rows are bound together by the sign └or┘ (in column 8). In the literature references the nucleus then appears under both mass numbers, e.g., ^{79,81}Se is to be read: either ^{79}Se or ^{81}Se. If the assignment of an activity is possible only above or below a given mass number, or not possible at all, this is indicated by > or < or ?. Several isotopes of this kind for the same element are distinguished from one another by right upper indices, e.g., $^{>82}$Br^1, $^{>82}$Br^2, $^{>82}$Br^3 or $^{?}$Kr^1, $^{?}$Kr^2. This distinction is made, also, when two activities might reasonably be assigned to the same mass number, without sufficient certainty existing for the assignment to make isomerism probable. Activities whose assignments to a given element are uncertain are not included in the tables.

The abundance, in per cent, of the isotopes of an element which are detectable by the mass spectrograph are contained in column 5. These have been computed from the data of Table I (relative abundances). Column 6 gives the best measured values of the half-lives of the unstable nuclei. The applicable paper is always cited in the literature references and, where an entry is missing (this applies to those isotopes of the disintegration series which have not recently been measured), the half-lives, as given in "Bericht der int. Radium-Standard-Kommission," *Physik. Z.*, **32**, 569 (1931), have been taken. The type of decay (α, β^+, β^-, K-capture, γ-emission) is given in column 7 (see sections 27–30 in the text). The relevant literature references are given only in the case of K-capture, double disintegration, or γ-decay. Column 8 contains measurements of the energy of the upper limit of the continuous β-spectrum in MeV. Here, the (partially contradictory) results of different authors have been taken, separated by semicolons (similarly in the references). Values which are separated only by a comma represent the upper limits of a complex spectrum, i.e., β-transitions to two (or three) different states of the daughter nucleus, where the difference should always be observed as γ-radiation. Usually the upper limits obtained by inspection (see page 86 of the text) have been taken (ordinary print), but, in some cases, the values extrapolated according to Konopinski and Uhlenbeck (so-called K.U. values) have been used (printed in *italics*). The energies of the corresponding observed γ-radiation in MeV for unstable nuclei have been collected in column 9 (even though the radiation is usually emitted by the daughter nucleus), regardless of whether the nuclei have experienced internal conversion (and so are observed as secondary β-particles) or not. From Tl on, the α-decay energies have been entered in this column (see page 80 of the text); γ-decay entries have been given special notation. Most of the α-decay energies of the naturally radioactive nuclei have been taken from Table 5 of K. Phillip's book, "Kernspektren" (*Hand- und Jahrbuch der chemischen Physik*, Bd. 9/V). Where more recent values have been included, this is indicated by giving the literature reference.* Columns 10 and 11 contain isotopic weights calculated from the data of Tables III and VI.†

* I should like to express my thanks to Professor Phillip for his kindness in arranging this material.

† For more information concerning this calculation, see pages 11 et seq. and 17 et. seq. of the text, as well as S. Flügge and J. Mattauch, *Physik. Z.*, **42**, 1 (1941).

Columns 12 to 25 are devoted to nuclear reactions. Even though the number of columns remains the same, the reaction types written at the top in ordinary (Bothe-Fleischmann) notation sometimes change from one page to the next according to the need. Where this has been necessitated by lack of space, a newly occurring reaction type has sometimes been put in an otherwise empty column. In this part of the tables, red print means the initial product, black print the end product of the reaction marked at the top of the column. The other reaction partner is always the isotope given on the right border of the table along the corresponding row; e.g., page 127, row for ^{10}B, column 13, is to be read as follows: $^{7}_{3}$Li$(\alpha, n)^{10}_{5}$B (literature reference under ^{10}B[13]) and $^{10}_{5}$B$(\alpha, n)^{13}_{7}$N (without literature reference). For this reason, every reaction appears twice (for example, the two in column 13 just mentioned, and also in the rows for ^{7}Li and ^{13}N), so that a single reference for the end product suffices. This setup in the tables permits us to obtain at a glance the initial isotopes (red print) and the reactions (at the head of the column) which produce a given nucleus (right edge of the table) as an end product, and, conversely, to see which nuclei (black print) could be obtained from a given initial isotope (right edge of the table) by what kind of reactions (head of column). As reactions which have in common the bombarding particle, as (n, γ), (n, α), (n, p), $(n, 2n)$, are as close to each other as possible, one can easily ascertain what result may be expected if, for example, a given element is bombarded by neutrons. Furthermore, reactions which lead from the same initial product to the same end product as, e.g., addition of a proton by (p, γ) or (d, n), neutron addition by (d, p) or (n, γ), neutron loss by $(n, 2n)$ or (γ, n), have been held as closely together as possible.

If the mass number of a symbol has been enclosed by parentheses, the reaction type is certain, but the assignment to the given isotope is not. If the entire symbol is parenthesized, it is not certain whether this reaction has been observed. In the column "rad. decay," only those decay chains have been entered for which the daughter substance has been actually observed. Here, also, red print means the initial product (the parent substance), black print the final product (daughter substance) of the nucleus given at the right edge of the table. The type of radioactive decay (α, β-, γ-decay or K-capture) which is meant can easily be determined with the help of column 7. The column "fission of" gives in red print those heavy nuclei which are split by neutrons (or possibly by γ-quanta) and give rise to the nucleus occurring in the row. The entry $^{235}_{92}$U or $^{238}_{92}$U means: splitting of uranium with slow (fast) neutrons (i.e., properly speaking, splitting of ^{236}U and ^{239}U; see text pages 71 et seq.). The fission products of heavy nuclei (black print) are not included among these because of lack of space, but are listed at the end of the tables (together with the decay series).

The literature references, so far as possible, are arranged historically for every reaction. Papers which concern these reactions, even though the relationship was not known at the time of publication, have also been entered, the correct assignment having been made later. In order to limit the size, however, old papers which, after determination of the nuclei and measurement of the reaction energy deal only with detailed questions, e.g., determination of cross sections, have generally been omitted. Publications of this type may be found in M. S. Livingston and H. A. Bethe, *Rev. Modern Phys.*, **9**, 245 (1937), or in the tables by K. Diebner and E. Grassmann, Leipzig, 1939, and *Physik. Z.*, **41**, 157 (1940).

Table V contains the few nuclear reactions and references which could not be included in the scheme of Table IV.

Finally, *Table VI* contains all the known material on the reaction energy, Q, of nuclear reactions. Observations of threshold values in (p, n) reactions have also been used. If only the threshold value has been given in the paper, this value multiplied by $(A/A + 1)$ has been entered under Q (see page 67 of the text).

The first colored *plate* contains packing fractions (curves A and B, values on the axis in black) and mass defects (curves C and D, values on the axis in red) as a function of mass number, A. In curve C (and D), the straight line going from left to right is the critical slope for α-instability (the line binding the zero point with the ^{4}He-point). *Plates II–VIII* give a representation in the N–Z diagram of the known atomic nuclei (giving the per cent abundance and the half-lives), the type of decay and the nuclear reactions carried out among them.

Translator's Note: The reader's attention is called to the use of cassiopeium (Cp) rather than lutecium, and of niobium (Nb) rather than columbium. This usage has been retained because the nature of the process used for reproducing the tables section does not permit extensive revisions. For the same reason the symbol for xenon appears as X rather than Xe.

Table I

Z	Element	Symbol	N	A	Activity	Spin i $\hbar$	Literature	Magnetic Moment μ $\hbar e/2 M_p c$	Literature
0	Neutron	n	1	1	β	1/2	theoret.	$-1.93_5 \pm 0.02$	A 2, F 3, P 4, H 13
1	Hydrogen	H	0	1	—	1/2	H 14, K 1	$+2.785 \pm 0.02$	K 3
		D	1	2	—	1	M 30	$+0.855 \pm 0.006$	K 3
2	Helium	He	1	3	—	—	—	—	—
			2	4	—	0	B 13	—	—
3	Lithium	Li	3	6	—	1	M 2	$+0.820 \pm 0.005$	R 2, R 3, M 22
			4	7	—	3/2	H 3, G 7, S 8, F 2	$+3.250 \pm 0.016$	R 2, R 3, M 22, J 4a
4	Beryllium	Be	5	9	—	—	—	$g\,[=\mu/i] = -0.783 \pm 0.003$	K 14
5	Boron	B	5	10	—	—	—	$g\,[=\mu/i] = +0.597 \pm 0.003$	M 23
			6	11	—	—	—	$g\,[=\mu/i] = +1.788 \pm 0.005$	M 23
6	Carbon	C	6	12	—	0	B 13	—	—
			7	13	—	(3/2)	T 8	$g\,[=\mu/i] = +1.401 \pm 0.004$ [1])	H 4
7	Nitrogen	N	7	14	—	1	O 3	$+0.402 \pm 0.002$	M 21, K 15
			8	15	—	1/2	K 13, W 3	$(-)\,0.280 \pm 0.003$	Z 1
8	Oxygen	O	8	16	—	0	B 13	—	—
			9	17	—	—	—	—	—
			10	18	—	—	—	—	—
9	Fluorine	F	10	19	—	1/2	G 1, C 1	$+2.622 \pm 0.014$	R 2, R 3, M 22
10	Neon	Ne	10	20	—	—	—	—	—
			11	21	—	—	—	—	—
			12	22	—	—	—	—	—
11	Sodium	Na	12	23	—	3/2	J 1, G 4, L 1, E 1, R 1	$+2.216 \pm 0.011$	K 15
12	Magnesium	Mg	12	24	—	—	—	—	—
			13	25	—	—	—	—	—
			14	26	—	—	—	—	—
13	Aluminum	Al	14	27	—	5/2	H 9, M 24	$+3.628 \pm 0.010$	M 24
14	Silicon	Si	14	28	—	—	—	—	—
			15	29	—	—	—	—	—
			16	30	—	—	—	—	—
15	Phosphorus	P	16	31	—	1/2	J 5a, A 5a	—	—
16	Sulfur	S	16	32	—	0	B 13	—	—
			17	33	—	—	—	—	—
			18	34	—	—	—	—	—
			20	36	—	—	—	—	—
17	Chlorine	Cl	18	35	—	5/2	E 2, S 33a	1.365 ± 0.005	K 16
			20	37	—	5/2	S 33a	1.135 ± 0.005	K 16
18	Argon	A	18	36	—	—	—	—	—
			20	38	—	—	—	—	—
			22	40	—	—	—	—	—
19	Potassium	K	20	39	—	3/2	M 18, F 2	$+0.391 \pm 0.002$	K 15
			21	40	β	—	N 4, H 7, S 35	—	—
			22	41	—	3/2	M 1	$+0.217 \pm 0.001$	M 1, K 15
20	Calcium	Ca	20	40	—	—	—	—	—
			22	42	—	—	—	—	—
			23	43	—	—	—	—	—
			24	44	—	—	—	—	—
			26	46	—	—	—	—	—
			28	48	—	—	—	—	—
21	Scandium	Sc	24	45	—	7/2	S 17, K 8	$+4.8$	K 11
22	Titanium	Ti	24	46	—	—	—	—	—
			25	47	—	—	—	—	—
			26	48	—	—	—	—	—
			27	49	—	—	—	—	—
			28	50	—	—	—	—	—

[1]) Consistent only with $i = 1/2$. Then $\mu = +0.700 \pm 0.002$. *Cf.* H 4 and also I 1.

Quadrupole Moment q 10^{-24} cm²	Literature	Relative Abundance	Literature	Packing Fraction f 10^{-4} MU	Mass Defect 10^{-3} MU	Mass Defect MeV	Average Mass Number	Chem. Atomic Weight for O = 16: Calc. from av. mass number	Chem. Atomic Weight for O = 16: Intern. Tables 1940	Z
—	—	—	—	+ 89.45 ± 0.25	—	—	—	—	—	0
— 2.73	— K 2	6970 ± 50 1	S 37 [1]	+ 81.31 ± 0.032 + 73.63 ± 0.032	— 2.35	— 2.19	1.0083	1.0080	1.0080	1
— —	— —	10^{-7} 1	A 1 [2]	+ 56.77 ± 0.18 + 9.65 ± 0.08	8.18 30.29	7.61 28.20	4.0038	4.0027	4.003	2
— —	— —	1 11.60 ± 0.06	B 18	+ 28.20 ± 0.09 + 25.95 ± 0.08	34.31 42.01	31.94 39.11	6.939	6.937	6.940	3
—	—	—	—	+ 16.62 ± 0.07	62.3	58.0	9.0150	9.0125	9.02	4
— —	— —	1 4.04	A 9	+ 16.17 ± 0.07 + 11.73 ± 0.05	69.2 81.4	64.4 75.8	10.814	10.81	10.82	5
— —	— —	89.3 ± 1 to 2% 1	M 29 [3]	+ 3.233 ± 0.020 + 5.82 ± 0.03	98.6 103.8	91.8 96.7	12.015	12.012	12.010	6
— —	— —	265 ± 8 1	V 6	+ 5.368 ± 0.013 + 3.29 ± 0.05	112.0 123.5	104.3 115.0	14.011	14.007	14.008	7
— — —	— — —	503 ± 10 — — 1 1 4.9 ± 0.2	S 34 M 28	0 per def. + 2.65 ± 0.04 + 2.73 ± 0.10	136.6 141.1 149.6	127.2 131.3 139.3	16.0044	16.0000	16.0000	8
—	—	—	—	+ 2.39 ± 0.06	158.1	147.2	19.0045	18.9993	19.00	9
— — —	337 ± 20, 9.25 ± 0.08 1 — — 1		V 6	— 0.553 ± 0.030 + 0.01 ± 0.1 — 0.65 ± 0.14	171.9 179.7 190.1	160.0 167.3 177.0	20.196	20.191	20.183	10
—	—	—	—	— 1.55 ± 0.08	200.3	186.5	22.996	22.990	22.997	11
— — —	— — —	6.7 — 1, 1.04 — 1	D 1	— 2.92 ± 0.16 — 2.15 ± 0.18 — 3.80 ± 0.1	211.9 219.2 232.7	197.3 204.1 216.6	24.330	24.323	24.32	12
—	—	—	—	— 3.45 ± 0.16	240.2	223.7	26.991	26.984	26.97	13
— — —	— — —	89.6 } tentative 6.2 } values 4.2 } values	M 11	— 4.56 ± 0.16 — 4.65 ± 0.21 — 5.34 ± 0.17	251.8 261.5 273.0	234.5 243.5 254.1	28.133	28.125	28.06	14
—	—	—	—	— 5.03 ± 0.09	280.7	261.3	30.984	30.976	30.974 [4]	15
— — — —	6000 ± 10%, 100 — — 1	0.78 ± 2% 4.4 ± 2% —	N 8	— 5.46 ± 0.08 — — 5.94 ± 0.11 —	290.7 — 311.3 —	270.6 — 289.8 —	32.074	32.065	32.06	16
— —	— —	3.07 ± 0.03 1	N 3	— 6.05 ± 0.06 — 6.03 ± 0.02	320.4 339.4	298.3 316.0	35.470	35.460	35.457	17
— — —	— — —	1, 5.1 — 1 325, —	N 2	— 6.31 ± 0.10 — 6.68 ± 0.09 — 6.127 ± 0.031	330.1 350.6 367.7	307.3 326.4 342.3	39.962	39.951	39.944	18
— — —	8600 ± 10%, 14.20 ± 0.03 1 — — 1		— N 4 B 19 [5]	— 6.1 ± 0.4 — — 6.58 or 6.22	357 — 378.3 or 376.8	333 — 352.2 or 350.8	39.131	39.097	39.096	19
— — — — — —	— — — — — —	100 0.66 ± 3% 0.150 ± 3% 2.13 ± 3% 0.0034 ± 15% 0.191 ± 3%	N 8	(— 6.2)	—	—	40.115	40.08	40.08	20
—	—	—	—	— 6.72 ± 0.14	415.7	387.0	45	44.96	45.10	21
— — — — —	— — — — —	10.82 ± 2% 10.56 ± 2% 100 7.50 ± 2% 7.27 ± 2%	N 8	— — — 7.13 ± 0.08 — 7.4 ± 0.4 — 7.4 ± 0.4	— — 445.7 457 466	— — 414.9 425 434	47.925	47.88	47.90	22

[1]) For ordinary Lake Michigan water. [2]) For spectroscopically pure (atmospheric) helium. [3]) For sea water (marine shells and limestone). [4]) New determination by H 11. [5]) From tests with ocean water of different origins and depths.

Table I

Z	Element	Symbol	N	A	Activity	Spin i $\hbar$	Literature	Magnetic Moment μ $\hbar\, e/2\, M_p\, c$	Literature
23	Vanadium	V	28	51	—	(7/2)	K 10	—	—
24	Chromium	Cr	26	50	—	—	—	—	—
			28	52	—	—	—	—	—
			29	53	—	—	—	—	—
			30	54	—	—	—	—	—
25	Manganese	Mn	30	55	—	5/2	W 2, F 1	3.0	F 1
26	Iron	Fe	28	54	—	—	—	—	—
			30	56	—	—	—	—	—
			31	57	—	—	—	—	—
			32	58	—	—	—	—	—
27	Cobalt	Co	32	59	—	7/2	K 9, M 25, R 5	2 to 3	M 25
28	Nickel	Ni	30	58	—	—	—	—	Intensity ratio of
			32	60	—	—	—	—	60/58 =
			33	61	—	—	—	—	62/60 =
			34	62	—	—	—	—	64/62 =
			36	64	—	—	—	—	64/61 =
29	Copper	Cu	34	63	—	3/2	R 7	+ 2.5 } $\mu^{65}/\mu^{63} = 1.04$	S 25, S 30
			36	65	—	3/2	R 7	+ 2.6	S 25, S 30
30	Zinc	Zn	34	64	—	—	—	—	—
			36	66	—	—	—	—	—
			37	67	—	5/2	L 6	+ 0.9	L 6
			38	68	—	—	—	—	—
			40	70	—	—	—	—	—
31	Gallium	Ga	38	69	—	3/2	J 1, C 2	+ 2.11 } $\mu^{71}/\mu^{69} = 1.270$	S 27, R 5a
			40	71	—	3/2	J 1, C 2	+ 2.69	S 27, R 5a
32	Germanium	Ge	38	70	—	—	—	—	—
			40	72	—	—	—	—	—
			41	73	—	—	—	—	—
			42	74	—	—	—	—	—
			44	76	—	—	—	—	—
33	Arsenic	As	42	75	—	3/2	T 2, C 5, C 6	+ 1.5	C 6, S 26
34	Selenium	Se	40	74	—	—	—	—	—
			42	76	—	—	—	—	—
			43	77	—	—	—	—	—
			44	78	—	—	—	—	—
			46	80	—	0	W 5	—	—
			48	82	—	—	—	—	—
35	Bromine	Br	44	79	—	3/2	T 1	2.6 } $\mu^{79}/\mu^{81} = 1.0$	T 1, S 4
			46	81	—	3/2	T 1	2.6	T 1, S 4
36	Krypton	Kr	42	78	—	—	—	—	—
			44	80	—	—	—	—	—
			46	82	—	—	—	—	—
			47	83	—	9/2	K 12	− 1.0	K 12, S 31
			48	84	—	—	—	—	—
			50	86	—	—	—	—	—
37	Rubidium	Rb	48	85	—	5/2	K 6, J 2, M 19	+ 1.345 ± 0.005	K 16
			50	87	β	3/2	H 1, M 4a, H 6	+ 2.741 ± 0.009	K 16
38	Strontium	Sr	46	84	—	—	—	—	—
			48	86	—	—	—	—	—
			49	87	—	9/2	H 8	− 1.1	H 8
			50	88	—	—	—	—	—
39	Yttrium	Y	50	89	—	—	—	—	—
40	Zirconium	Zr	50	90	—	—	—	—	—
			51	91	—	—	—	—	—
			52	92	—	—	—	—	—
			54	94	—	—	—	—	—
			56	96	—	—	—	—	—
41	Niobium (Columbium)	Nb (Cb)	52	93	—	9/2	B 11	(3.7)	B 11

Table I

Quadrupole Moment q 10^{-24} cm²	Literature	Relative Abundance	Literature	Packing Fraction f 10^{-4} MU	Mass Defect 10^{-3} MU	Mass Defect MeV	Average Mass Number	Chem. Atomic Weight for O = 16: Calc. from av. mass number	Chem. Atomic Weight for O = 16: Intern. Tables 1940	Z
—	—	—	—	− 7.78 ± 0.12	477.1	444.2	51	50.95	50.95	23
— — — —	— — — —	5.36 100 11.26 2.75	N 12	— − 7.9 ± 0.2 — —	— 487 — —	— 453 — —	52.051	52.00	52.01	24
—	—	—	—	(− 7.3)	—	—	55	54.94	54.93	25
— — — —	— — — —	6.37 100 2.37 0.34	V 2 (N 12)	− 7.3 ± 0.4 − 7.7 ± 0.3 — —	501 523 — —	466 487 — —	55.911	55.85	55.85	26
—	—	or	—	(− 7.0)	—	—	59	58.94	58.94	27
the mass numbers: 0.470 ± 0.020 0.154 ± 0.007 0.272 ± 0.01 0.745 ± 0.015		62.8 67.4 29.5 26.7 1.7 1.2 4.7 3.8 1.3 0.88	V 3 S 36; (G 2)	— 6.95 ± 0.07 — 8.37 ± 0.06 — 7.5 ± 0.3 — 8.13 ± 0.06 — 8.21 ± 0.09	536.3 564.1 568.8 582.2 602.2	499.3 525.2 529.6 542.1 560.7	58.861 58.84 after S 36; or 58.720 58.71 after V 3		58.69	28
−0.1 ± 0.1 −0.1 ± 0.1	S 25 S 25	2.5 1	A 6	− 6.9 ± 0.2 − 6.9 ± 0.2	583 603	543 561	63.64	63.58	63.57	29
— — — — —	— — — — —	50.9 27.3 3.9 17.4 0.5	N 4	− 6.7 ± 0.4 − 7.2 ± 0.4 — − 6.6 ± 0.5 − 6.6 ± 0.5	591 613 — 629 648	550 571 — 586 603	65.389	65.33	65.38	30
0.20 0.13	R 5a R 5a	61.2 ± 1% 38.8 ± 1%	S 1	− 6.4 ± 0.5 − 6.5 ± 0.5	636 656	592 611	69.776	69.71	69.72	31
— — — — —	— — — — —	21.2 27.3 7.9 37.1 6.5	A 8, B 5, B 6, A 9	(− 6.7)	—	—	72.657	72.59	72.60	32
+ 0.3	S 26	—	—	(− 6.9)	—	—	75	74.93	74.91	33
— — — — — —	— — — — — —	1.8 20.0 17.4 50.1 100 19.5	A 8	(− 7.2)	—	—	79.023	78.94	78.96	34
— —	— —	1 0.975 ± 0.025	B 17	(− 7.3)	—	—	79.988	79.91	79.916	35
— — — + 0.15 — —	— — — K 12, S 30 — —	0.608 ± 2% 3.52 ± 1% 20.2 ± 1% 20.2 ± 1% 100 30.6 ± 1%	N 7	− 7.0 ± 0.2 — − 7.5 ± 0.2 — − 7.3 ± 0.2 − 7.1 ± 0.2	724 — 756 — 783 801	674 — 713 — 729 746	83.902	83.82	83.7	36
— —	— —	2.68 ± 0.02 1	N 4	(− 7.2)	—	—	85.544	85.46	85.48	37
— — — —	— — — —	0.68 ± 2% 11.94 ± 1% 8.50 ± 1% 100	N 9	(− 6.9)	—	—	87.710	87.63	87.63	38
—	—	—	—	(− 6.7)	—	—	89	88.92	88.92	39
— — — — —	— — — — —	48 11.5 22 17 1.5	A 11	(− 6.4)	—	—	91.325	91.24	91.22	40
—	—	—	—	(− 6.2)	—	—	93	92.92	92.91	41

Table I

Z	Element	Symbol	N	A	Activity	Spin i $\hbar$	Literature	Magnetic Moment μ $\hbar\, e/2\, M_p\, c$	Literature
42	Molybdenum	Mo	50	92	—	—	—	—	—
			52	94	—	—	—	—	—
			53	95	—	—	—	—	—
			54	96	—	—	—	—	—
			55	97	—	—	—	—	—
			56	98	—	—	—	—	—
			58	100	—	—	—	—	—
44	Ruthenium	Ru	52	96	—	—	—	—	—
			54	98	—	—	—	—	—
			55	99	—	—	—	—	—
			56	100	—	—	—	—	—
			57	101	—	—	—	—	—
			58	102	—	—	—	—	—
			60	104	—	—	—	—	—
45	Rhodium	Rh	58	103	—	—	—	—	—
46	Palladium	Pd	56	102	—	—	—	—	—
			58	104	—	—	—	—	—
			59	105	—	—	—	—	—
			60	106	—	—	—	—	—
			62	108	—	—	—	—	—
			64	110	—	—	—	—	—
47	Silver	Ag	60	107	—	1/2	J 4	-0.10 } $\mu^{109}/\mu^{107} = 1.93$	J 4
			62	109	—	1/2	J 4	-0.19	J 4
48	Cadmium	Cd	58	106	—	—	—	—	—
			60	108	—	—	—	—	—
			62	110	—	—	—	—	—
			63	111	—	1/2	S 7, S 9, S 13	-0.65 } $\mu^{113}/\mu^{115} = 1.0$	J 6, B 13
			64	112	—	—	—		—
			65	113	—	1/2	S 7, S 9, S 13	-0.65	J 6, B 13
			66	114	—	—	—	—	—
			68	116	—	—	—	—	—
49	Indium	In	64	113	—	9/2	B 1, M 20	$+6.4$	B 1, M 20
			66	115	—	9/2	J 3, P 1, M 20	$+5.43 \pm 0.03$	H 2
50	Tin	Sn	62	112	—	—	—	—	—
			64	114	—	—	—	—	—
			65	115	—	—	—	—	—
			66	116	—	—	—	—	—
			67	117	—	1/2	T 3, S 14	-0.89 } $\mu^{117}/\mu^{119} = 1.0$	T 3
			68	118	—	—	—		—
			69	119	—	1/2	T 3, S 14	-0.89	T 3
			70	120	—	—	—	—	—
			72	122	—	—	—	—	—
			74	124	—	—	—	—	—
51	Antimony	Sb	70	121	—	5/2	B 3, T 4, C 6	3.7 } $\mu^{121}/\mu^{123} = 1.316$	C 6, B 13 } T 7
			72	123	—	7/2	B 3, C 6	2.8	C 6, B 13
52	Tellurium	Te	68	120	—	—	—	—	—
			70	122	—	—	—	—	—
			71	123	—	—	—	—	—
			72	124	—	—	—	—	—
			73	125	—	—	—	—	—
			74	126	—	—	—	—	—
			76	128	—	—	—	—	—
			78	130	—	—	—	—	—
53	Iodine	I	74	127	—	5/2	T 5, M 26	2,8	S 5
54	Xenon	X (Xe)	70	124	—	—	—	—	—
			72	126	—	—	—	—	—
			74	128	—	—	—	—	—
			75	129	—	1/2	K 7, J 7	-0.9 } $\mu^{129}/\mu^{131} = -1.11$	K 7, J 7, B 13
			76	130	—	—	—		—
			77	131	—	3/2	K 7, J 7	$+0.8$	K 7, J 7, B 13
			78	132	—	—	—	—	—
			80	134	—	—	—	—	—
			82	136	—	—	—	—	—

Quadrupole Moment q 10^{-24} cm²	Literature	Relative Abundance	Literature	Packing Fraction f 10^{-4} MU	Mass Defect 10^{-3} MU	Mass Defect MeV	Average Mass Number	Chem. Atomic Weight for O = 16: Calc. from av. mass number	Chem. Atomic Weight for O = 16: Intern. Tables 1940	Z
—	—	14.9 ± 1%	V 1 (L 3)	—	—	—	96.004	95.92	95.95	42
—	—	9.40 ± 1%		− 5.8 ± 0.5	862	803				
—	—	16.1 ± 1%		− 5.8 ± 0.5	871	811				
—	—	16.6 ± 1%		− 5.6 ± 0.5	879	818				
—	—	9.65 ± 1%		− 5.7 ± 0.3	889	828				
—	—	24.1 ± 1%		− 5.7 ± 0.3	899	837				
—	—	9.25 ± 1%		− 6.1 ± 0.3	922	858				
—	—	5	A 8	− 5.7 ± 0.3	878	817	101.180	101.10	101.7	44
—	—	?		—	—	—				
—	—	12		− 5.7 ± 0.3	906	843				
—	—	14		—	—	—				
—	—	22		—	—	—				
—	—	30		—	—	—				
—	—	17		—	—	—				
—	—	—	—	− 5.0 ± 0.5	936	871	103	102.92	102.91	45
—	—	0.8 ± 1%	S 2	—	—	—	106.631	106.55	106.7	46
—	—	9.3 ± 1%		—	—	—				
—	—	22.6 ± 1%		—	—	—				
—	—	27.2 ± 1%		− 5.1 ± 0.4	965	898				
—	—	26.8 ± 1%		—	—	—				
—	—	13.5 ± 1%		− 5.1 ± 0.4	1003	934				
—	—	52.5	A 11	− 4.7 ± 0.3	969	902	107.950	107.87	107.880	47
—	—	47.5		− 4.7 ± 0.3	988	920				
—	—	1.4	N 4	(− 5.0)	—	—	112.465	112.38	112.41	48
—	—	1.0								
—	—	12.8								
—	—	13.0								
—	—	24.2								
—	—	12.3								
—	—	28.0								
—	—	7.3								
—	—	1	B 16, S 1	(− 4.9)	—	—	114.910	114.82	114.76	49
+ 0.82	B 1. S,28	21 ± 1								
—	—	1.1	A 7, B 8, A 12	—	—	—	118.785	118.70	118.70	50
—	—	0.8		—	—	—				
—	—	0.4		—	—	—				
—	—	15.5		− 4.9 ± 0.4	1054	981				
—	—	9.1		—	—	—				
—	—	22.5		− 5.1 ± 0.3	1075	1001				
—	—	9.8		− 5.2 ± 0.3	1086	1011				
—	—	28.5		—	—	—				
—	—	5.5		− 4.4 ± 0.4	1105	1029				
—	—	6.8		− 4.4 ± 0.4	1124	1046				
no	T 7	100	A 8	(− 4.7)	—	—	121.880	121.79	121.76	51
yes	T 7	78.5								
—	—	very rare	D 4	(− 4.4)	—	—	127.668	127.58	127.61	52
—	—	2.9	B 4, A 8							
—	—	1.6								
—	—	4.5								
—	—	6.0								
—	—	19.0								
—	—	32.8								
—	—	33.1								
− 0.4$_6$ ± 0.15	S 5, S 6, M 27	—	—	(− 4.4)	—	—	127	126.91	126.92	53
—	—	0.347 ± 3%	N 7	—	—	—	131.400	131.31	131.3	54
—	—	0.327 ± 3%		—	—	—				
—	—	7.06 ± 1%		—	—	—				
—	—	97.3 ± 1%		− 4.2 ± 0.1	1164	1084				
—	—	15.1 ± 1%		—	—	—				
0 ± 0.1	K 12, S 30	78.5 ± 1%		—	—	—				
—	—	100.0		− 4.1	1191	1109				
—	—	39.1 ± 1%		—	—	—				
—	—	33.2 ± 1%		—	—	—				

Table I

Z	Element	Symbol	N	A	Activity	Spin i $\hbar$	Literature	Magnetic Moment μ $\hbar\, e/2\, M_p\, c$	Literature
55	Cesium	Cs	78	133	—	7/2	K 4, C 4	$+ 2.572 \pm 0.013$	K 15
56	Barium	Ba	74	130	—	—	—	—	—
			76	132	—	—	—	—	—
			78	134	—	—	—	$g^{137}/g^{135} = 1.1174 \pm 0.1\%$	H 5
			79	135	—	3/2	B 12	$g\,[=\mu/i] = + 0.558 \pm 0.002$	H 5
			80	136	—	—	—	$\mu^{135} = + 0.837 \pm 0.003$	H 5
			81	137	—	(3/2)	B 12	$g\,[=\mu/i] = + 0.624 \pm 0.002$	H 5
			82	138	—	—	—	$\mu^{137} = +(0.936 \pm 0.003)$	H 5
57	Lanthanum	La	82	139	—	7/2	A 3	2.5 2.8	A 4, C 7, C 8
58	Cerium	Ce	78	136	—	—	—	—	—
			80	138	—	—	—	—	—
			82	140	—	—	—	—	—
			84	142	—	—	—	—	—
59	Praseodymium	Pr	82	142	—	5/2	W 1 a	—	—
60	Neodymium	Nd	82	142	—	—	—	—	Intensity ratio of
			83	143	—	—	—	—	142/144 =
			84	144	—	—	—	—	142/146 =
			85	145	—	—	—	—	146/143 =
			86	146	—	—	—	—	143/145 =
			88	148	—	—	—	—	145/148 =
			90	150	—	—	—	—	148/150 =
62	Samarium	Sm (Sa)	82	144	—	—	—	—	—
			85	147	—	—	—	—	—
			86	148	α	—	W 2 a	—	—
			87	149	—	—	—	—	—
			88	150	—	—	—	—	—
			90	152	—	—	—	—	—
			92	154	—	—	—	—	—
63	Europium	Eu	88	151	—	5/2	S 20	3.4 $\mu^{151}/\mu^{153} = 2.24$	S 20, S 4
			90	153	—	5/2	S 20	1.5	S 20, S 4
64	Gadolinium	Gd	88	152	—	—	—	—	—
			90	154	—	—	—	—	—
			91	155	—	—	—	—	—
			92	156	—	—	—	—	—
			93	157	—	—	—	—	—
			94	158	—	—	—	—	—
			96	160	—	—	—	—	—
65	Terbium	Tb	94	159	—	3/2	S 16	—	—
66	Dysprosium	Dy	92	158	—	—	—	—	—
			94	160	—	—	—	—	—
			95	161	—	—	—	—	—
			96	162	—	—	—	—	—
			97	163	—	—	—	—	—
			98	164	—	—	—	—	—
67	Holmium	Ho	98	165	—	7/2	S 21	—	—
68	Erbium	Er	94	162	—	—	—	—	—
			96	164	—	—	—	—	—
			98	166	—	—	—	—	—
			99	167	—	—	—	—	—
			100	168	—	—	—	—	—
			102	170	—	—	—	—	—
69	Thulium	Tm	100	169	—	1/2	S 18	—	—
70	Ytterbium	Yb	98	168	—	—	—	—	—
			100	170	—	—	—	—	—
			101	171	—	1/2	S 30	$+ 0.4_5$ $\mu^{173}/\mu^{171} = 1.4$	S 31
			102	172	—	—	—		—
			103	173	—	5/2	S 30	$- 0.6_5$	S 31
			104	174	—	—	—	—	—
			106	176	—	—	—	—	—

Table I

Quadrupole Moment q 10^{-24} cm²	Literature	Relative Abundance	Literature	Packing Fraction f 10^{-4} MU	Mass Defect 10^{-3} MU	Mass Defect MeV	Average Mass Number	Chem. Atomic Weight for O = 16: Calc. from av. mass number	Chem. Atomic Weight for O = 16: Intern. Tables 1940	Z
< |0.3|	S6a, K4	—	—	(— 4.0)	—	—	133	132.91	132.91	55
—	—	0.141 ± 4%	N 9	(— 3.7)	—	—	137.422	137.33	137.36	56
—	—	0.136 ± 4%								
—	—	3.37 ± 2%								
—	—	9.2 ± 2%								
—	—	10.9 ± 2%								
—	—	15.8 ± 2%								
—	—	100								
—	—	—	—	— 3.2 ± 0.2	1241	1155	139	138.92	138.92	57
—	—	rare	D 3	(— 3.5)	—	—	140.22	140.13	140.13	58
—	—	rare								
—	—	89	A 10							
—	—	11								
—	—	—	—	(— 3.4)	—	—	141	140.91	140.92	59
the mass numbers:		25.9_5	M 6	—	—	—	144.402	144.32	144.27	60
1.15 ± 0.01		13.0		—	—	—				
1.57 ± 0.03		22.6		—	—	—				
1.27 ± 0.03		9.2		—	—	—				
1.42 ± 0.02		16.5		— 2.5 ± 0.2	1294	1204				
1.34 ± 0.03		6.8		— 2.4 ± 0.2	1311	1220				
1.15 ± 0.01		5.9_5		— 2.0 ± 0.2	1323	1232				
—	—	3	A 10	(— 2.4)	—	—	150.200	150.12	150.37 [1]	62
—	—	17								
—	—	14								
—	—	15								
—	—	5								
—	—	26								
—	—	20								
~ + 1.2	S20, C3, S 30	96.3 ± 1.2	L 2	(— 2.2)	—	—	152.020	151.94	152.0	63
~ + 2.5		100								
—	—	0.2%	D 7	—	—	—	157.005	156.94	156.9	64
—	—	1.5%		—	—	—				
—	—	21	A 10	— 1.5 ± 0.2	1358	1264				
—	—	23		— 1.5 ± 0.2	1367	1273				
—	—	17		— 1.5 ± 0.2	1376	1281				
—	—	23		— 1.5 ± 0.2	1386	1290				
—	—	16		— 1.5 ± 0.2	1404	1307				
—	—	—	—	(— 1.4)	—	—	159	158.93	159.2	65
—	—	0.1%	D 7	(— 1.0)	—	—	162.548	162.49	162.46	66
—	—	1.5%								
—	—	22	A 10							
—	—	25								
—	—	25								
—	—	28								
—	—	—	—	(— 0.8)	—	—	165	164.94	164.94 [2]	67
—	—	0.25%	D 7	(— 0.6)	—	—	167.167	167.11	167.2	68
—	—	2%								
—	—	36	A 10							
—	—	24								
—	—	30								
—	—	10								
—	—	—	—	(— 0.4)	—	—	169	168.95	169.4	69
—	—	0.06	D 7	(— 0.0)	—	—	173.068	173.02	173.04	70
—	—	4.21	W 1							
—	—	14.26								
—	—	21.49								
+ 3.9 ± 0.4	S 30	17.02								
—	—	29.58								
—	—	13.38								

[1]) O. Hönigschmid, private communication. [2]) New determination by H 12.

Table I

Z	Element	Symbol	N	A	Activity	Spin i $\hbar$	Literature	Magnetic Moment μ $\hbar\, e/2\, M_p\, c$	Literature
71	Cassiopeium	Cp	104	175	—	7/2	S 22, G 3	+ 2.6 ± 0.5	G 3
	(Lutecium)	(Lu)	105	176	β	⩾ 7	H 10, M 9, L 4, S 32	+ 3.8 ± 0.7	S 32
72	Hafnium	Hf	102	174	—	—	—	—	—
			104	176	—	—	—	—	—
			105	177	—	(⩽3/2)	R 4	—	—
			106	178	—	—	—	—	—
			107	179	—	(⩽3/2)	R 4	—	—
			108	180	—	—	—	—	—
73	Tantalum	Ta	108	181	—	7/2	M 15	—	—
74	Tungsten	W	106	180	—	—	—	—	—
			108	182	—	—	—	—	—
			109	183	—	—	—	—	—
			110	184	—	—	—	—	—
			112	186	—	—	—	—	—
75	Rhenium	Re	110	185	—	5/2	M 16, M 17, G 6	+ 3.3	S 29, S 30
			112	187	—	5/2	Z 2	+ 3.3 $\mu^{187}/\mu^{185} = 1.011$	S 29, S 30
76	Osmium	Os	108	184	—	—	—	—	—
			110	186	—	—	—	—	—
			111	187	—	—	—	—	—
			112	188	—	—	—	—	—
			113	189	—	—	—	—	—
			114	190	—	—	—	—	—
			116	192	—	—	—	—	—
77	Iridium	Ir	114	191	—	1/2	V 2	$\mu^{191}/\mu^{193} = -1.0$	V 2
			116	193	—	3/2	V 2		
78	Platinum	Pt	114	192	—	—	—	—	—
			116	194	—	—	—	—	—
			117	195	—	1/2	F 4, V 1, J 5, T 6	+ 0.6	J 5, T 6, S 3
			118	196	—	—	—	—	—
			120	198	—	—	—	—	—
79	Gold	Au	118	197	—	(3/2)	R 6, W 4	+ 0.3	R 6, W 4, S 19, B 13
80	Mercury	Hg	116	196	—	—	—	—	—
			118	198	—	—	—	—	—
			119	199	—	1/2	S 11, S 12	+ 0.547 ± 0.002	M 25a
			120	200	—	—	—	$\mu^{199}/\mu^{201} = -0.9018$	S 19
			121	201	—	3/2	S 11, S 12	− 0.607 ± 0.003	M 25a
			122	202	—	—	—	—	—
			124	204	—	—	—	—	—
81	Thallium	Tl	122	203	—	1/2	M 12, M 13	+ 1.45	S 28
			124	205	—	1/2	S 10	+ 1.45 $\mu^{205}/\mu^{203} = 1.0097$	S 28
82	Lead	Pb	122	204	—	—	—	—	—
			124	206	—	—	—	—	—
			125	207	—	1/2	K 5	+ 0.6	M 14, R 8, S 19, B 13
			126	208	—	—	—	—	—
83	Bismuth	Bi	126	209	—	9/2	B 2	+ 3.6	S 19, S 30
84	Polonium	Po	126	210	α	—	—	—	—
		AcC′	127	211	α	—	—	—	—
		ThC′	128	212	α	—	—	—	—
		RaC′	130	214	α	—	—	—	—
		AcA	131	215	α	—	—	—	—
		ThA	132	216	α	—	—	—	—
		RaA	134	218	α	—	—	—	—
86	Actinon	An	133	219	α	—	—	—	—
	Thoron	Tn	134	220	α	—	—	—	—
	Radon	Rn	136	222	α	—	—	—	—
87		AcK	136	223	β	—	P 2, P 3	—	—

Table I

Quadrupole Moment q 10^{-24} cm²	Literature	Relative Abundance	Literature	Packing Fraction f 10^{-4} MU	Mass Defect 10^{-3} MU	Mass Defect MeV	Average Mass Number	Chem. Atomic Weight for O = 16: Calc. from av. mass number	Chem. Atomic Weight for O = 16: Intern. Tables 1940	Z
+ 5.9	G 3	100	M 9	(+ 0.2)	—	—	175.025	174.98	174.99	71
+ 6 to 8	S 32	2.58 ± 0.07								
—	—	0.3 %	D 9	(+ 0.5)	—	—	178.477	178.44	178.6	72
—	—	5	A 11							
—	—	19								
—	—	28								
—	—	18								
—	—	30								
~ + 6	S 6a	—	—	(+ 0.8)	—	—	181	180.96	180.88	73
—	—	— 0.01	D 5	(+ 1.0)	—	—	183.963	183.93	183.92	74
—	—	74.8 —	A 8							
—	—	57.1 1								
—	—	100 —								
—	—	99 —								
+ 2.8	S29, S30	1	A 8	(+ 1.2)	—	—	186.236	186.21	186.31	75
+ 2.6	S29, S30	1.62								
—	—	0.043 ± 10 %	N 6	(— 1.6)	—	—	190.276	190.25	190.2	76
—	—	3.87 ± 3 %								
—	—	4.01 ± 3 %								
—	—	32.4 ± 1 %								
—	—	39.4 ± 1 %								
—	—	64.4 ± 1 %		+ 2.0 ± 0.9	1600	1490				
—	—	100		+ 2.0 ± 0.3	1618	1506				
—	—	38.5	S 2	+ 2.0 ± 0.5	1608	1497	192.230	192.22	193.1	77
—	—	61.5		+ 2.0 ± 0.5	1625	1513				
—	—	0.8 ± 1 %	S 2	—	—	—	195.156	195.14	195.23	78
—	—	30.2 ± 1 %		+ 2.0 ± 0.3	1633	1520				
—	—	35.3 ± 1 %		+ 2.0 ± 0.2	1642	1529				
—	—	26.6 ± 1 %		+ 2.0 ± 0.4	1651	1537				
—	—	7.2 ± 1 %		+ 2.2 ± 0.3	1664	1549				
—	—	—	—	+ 2.0 ± 0.3	1659	1545	197	196.99	197.2	79
—	—	0.50 ± 3 %	N 7	(+ 2,4)	—	—	200.613	200.61	200.61	80
—	—	34.2 ± 1 %								
—	—	57.6 ± 1 %								
—	—	78.7 ± 1 %								
+ 0.5	S 23	44.6 ± 1 %								
—	—	100								
—	—	22.7 ± 1 %								
—	—	0.410 ± 2 %	N 9	+ 2.9 ± 0.5	1692	1575	204.413	204.42	204.39	81
—	—	1		+ 2.9 ± 0.5	1710	1592				
—	—	1.000	N 10[1])	+ 3.0 ± 0.5	1698	1581	207.242	207.24	207.21	82
—	—	15.93 ± 0.5 %		—	—	—				
—	—	15.30 ± 0.5 %		—	—	—				
—	—	35.3 ± 0.5 %		+ 2.9 ± 0.4	1734	1614				
— 0.39	S 24	—	—	+ 2.7 ± 0.4	1747	1626	209	209.00	209.00	83
—	—	—	—	+ 2.90	1750	1629	—	210.00	—	84
—	—	—	—	+ 3.18	1752	1631	—	—	—	
—	—	—	—	+ 3.25	1759	1638	—	—	—	
—	—	—	—	+ 3.55	1770	1649	—	—	—	
—	—	—	—	+ 3.77	1774	1653	—	—	—	
—	—	—	—	+ 3.94	1779	1658	—	—	—	
—	—	—	—	+ 4.27	1789	1667	—	—	—	
—	—	—	—	+ 4.25	1796	1673	—	—	—	
—	—	—	—	+ 4.32	1803	1679	—	—	—	
—	—	—	—	+ 4.59	1813	1688	—	222.04	—	86
—	—	—	—	+ 4.62	1820	1694	—	—	—	87

[1]) For lead sources geologically very old (pre-Cambrian origin).

Table I

Z	Element	Symbol	N	A	Activity	Spin i $\hbar$	Literature	Magnetic Moment $\hbar e/2 M_p c$	Literature
88	Radium	AcX	135	223	α	—	—	—	—
		ThX	136	224	α	—	—	—	—
		Ra	138	226	α	—	—	—	—
89	Actinium	Ac	138	227	β,α	—	P 2	—	—
90	Thorium	RdAc	137	227	α	—	—	—	—
		RdTh	138	228	α	—	—	—	—
		Io	140	230	α	—	—	—	—
		Th	142	232	α	—	—	—	—
91	Protoactinium	Pa	140	231	α	3/2	S 15	—	—
92	Uranium	U II	142	234	α	—	—	—	—
		AcU	143	235	α	—	—	—	—
		U I	146	238	α	—	—	—	—

Table II

Element	A	Maximal abundance in per cent	Literature
1 H	3	10^{-10}	S 33
2 He	5	0.0001	B 15
3 Li	5	0.001	S 1
4 Be	8	0.001	N 7
10 Ne	23	0.001	B 14
11 Na	20, 21, 22, 24, 25	0.002	B 20
16 S	30, 35	0.002	N 8
	31	0.005	
	37, 38	0.0005	
17 Cl	39	0.004	N 3
18 A	37	0.005	N 4
	39, 41	0.01	
	42	0.0003	N 8
19 K	42, 43	0.0006	N 1
20 Ca	38	0.0017	N 8
	39	0.0025	
	41	0.0007	
	45, 47, 49, 50	0.0005	
22 Ti	42, 51, 52, 53	0.0007	N 8
	43	0.007	
	44, 45	0.0014	
	54	0.003	
24 Cr	49, 51, 56	0.001	N 12
	55	0.006	
25 Mn	53, 57	0.007	S 2
26 Fe	52, 53	0.002	N 12
	55	0.005	
	59	0.013	
	60	0.003	
27 Co	57	0.17	S 2
30 Zn	63	0.0013	N 4
	65	0.0025	
	69	0.0017	
33 As	71, 72, 73, 77, 78, 79	0.001	N 7
	74	0.005	
	76	0.002	
35 Br	73, 87	0.004	N 5
	74, 86	0.008	
	75, 84, 85	0.013	
	76	0.017	
	77, 83	0.03	
	78, 82	0.25	
	80	0.05	
36 Kr	76, 77, 79, 81, 88	0.0012	N 7
	87	0.0023	
37 Rb	80, 81, 89, 90	0.0007	N 4
	83	0.0012	
	84	0.0060	
	86	0.0056	
	88	0.0033	
38 Sr	80, 81, 82	0.0004	N 9
	83, 89	0.0008	
	85	0.0017	
	90, 91, 92	0.0003	
39 Y	91	0.05	D 9
41 Nb	91, 95	0.25	S 2
42 Mo	88—91, 93, 99, 102—105	0.02	M 10
	101	0.03	
45 Rh	101	0.08	S 2
	105	0.10	

Table I

Quadrupole Moment q 10^{-24} cm²	Literature	Relative Abundance	Literature	Packing Fraction f 10^{-4} MU	Mass Defect 10^{-3} MU	Mass Defect MeV	Average Mass Number	Chem. Atomic Weight for O = 16: Calc. from av. mass number	Chem. Atomic Weight for O = 16: Intern. Tables 1940	Z
—	—	—	—	+ 4.62	1820	1694	—	—	—	
—	—	—	—	+ 4.73	1825	1699	—	—	—	
—	—	—	—	+ 4.96	1838	1711	—	226.05	226.05	88
—	—	—	—	+ 5.02	1845	1718	227	227.05	—	89
—	—	—	—	+ 4.98	1845	1718	—	—	—	
—	—	—	—	+ 5.09	1850	1723	—	—	—	
—	—	—	—	+ 5.35	1862	1734	—	—	—	
—	—	—	—	+ 5.60	1873	1744	—	232.06	232.12	90
—	—	—	—	+ 5.45	1868	1739	231	231.06	231	91
—	1	—	N 11	+ 5.60	1886	1756	237.978	238.06	238.07	92
—	—	1		+ 5.79	1891	1762				
—	17.000 ± 10 %, 139 ± 1 %			+ 6.18	1908	1776				

Table II

Element	A	Maximal abundance in per cent	Literature
48 Cd	107, 109	0.043	N 4
	115	0.125	
	118	0.0068	
49 In	110, 111	0.01	S 1
	112, 116, 117	0.02	
	114	0.5	
	118	0.012	
	119	0.003	
53 I	123, 124, 125	0.002	N 7
	126	0.004	
	128	0.007	
	129	0.0025	
	130	0.0008	
	131	0.0004	
54 X (Xe)	122, 123, 125	0.00045	N 7
	127	0.0009	
	133, 135, 137, 138	0.0018	
55 Cs	129, 130, 136, 137	0.001	N 7
	131	0.005	
	132	0.025	
	134	0.017	
	135	0.002	
56 Ba	128, 129, 131, 133, 140, 141	0.0007	N 9
	139	0.002	
	142	0.0004	
71 Cp(Lu)	177	0.1	D 9
73 Ta	179	0.1	D 9
76 Os	182, 183, 185	0.003	N 6
	191	0.011	
	193	0.007	
	194	0.004	
79 Au	199	0.01	D 2
80 Hg	194, 195	0.0015	N 7
	197	0.0037	
	203	0.0006	N 9
	205, 206	0.0016	N 7
81 Tl	199—201, 206—209	0.002	N 9
	203, 204	0.003	
82 Pb	203	0.002	N 5
	205	0.01	
	209	0.0009	
	210	0.009	
83 Bi	205—207, 211—213	0.001	N 9
	208, 210	0.002	
92 U	231—233, 236	0.003	N 11
	237, 239	0.0083	
	240—242	0.0016	

Table III

	A	Doublet	ΔM 10^{-4} MU	Lit.
^{1}H, ^{2}D, ^{12}C	2	$^{1}H_2-{}^{2}D$	15.2 ± 0.4	A 13
	2	$^{1}H_2-{}^{2}D$	15.3 ± 0.4	B 7, L 5
	2	$^{1}H_2-{}^{2}D$	15.39 ± 0.021	M 8
	6	$^{2}D_3-{}^{12}C^{2+}$	423.6 ± 1.2	A 13
	6	$^{2}D_3-{}^{12}C^{2+}$	421.9 ± 0.5	B 9, L 5
	6	$^{2}D_3-{}^{12}C^{2+}$	422.39 ± 0.21	M 8
	16	$^{12}C^{1}H_4-{}^{16}O$	360.1 ± 1.6	A 13
	16	$^{12}C^{1}H_4-{}^{16}O$	364.9 ± 0.8	J 8, L 5
	16	$^{12}C^{1}H_4-{}^{16}O$	364.06 ± 0.40	M 8
	16	$^{12}C^{1}H_4-{}^{16}O$	364.2 ± 0.9	A 5
^{4}He	6	$^{4}He_2-{}^{16}O^{2+}$	77.2 ± 1.2	B 10
	4	$^{2}D_2-{}^{4}He$	255.1 ± 0.8	A 13
	4	$^{2}D_2-{}^{4}He$	256.1 ± 0.4	B 9, L 5
^{7}Li	7	$^{7}Li-{}^{14}N^{2+}$	144.3 ± 1	B 9, L 5
^{9}Be	10	$^{9}Be^{1}H-{}^{10}B$	69.6 ± 2.0	J 10, L 5
	10	$^{9}Be^{1}H-{}^{20}Ne^{2+}$	239.1 ± 2.0	J 10, L 5
^{10}B	10	$^{10}B-{}^{20}Ne^{2+}$	168.4 ± 1.5	A 13
	10	$^{10}B-{}^{20}Ne^{2+}$	167.5 ± 1.5	J 10, L 5
	12	$^{10}B^{1}H_2-{}^{12}C$	287.5 ± 2.0	J 10, L 5
^{11}B	11	$^{10}B^{1}H-{}^{11}B$	116.0 ± 1.0	J 10, L 5
	12	$^{11}B^{1}H-{}^{12}C$	171.4 ± 1.0	J 10, L 5
^{13}C	13	$^{12}C^{1}H-{}^{13}C$	45 ± 1	B 7, L 5
	13	$^{12}C^{1}H-{}^{13}C$	44.7	M 5
^{14}N	14	$^{12}C^{1}H_2-{}^{14}N$	124.5 ± 0.7	A 13
	14	$^{12}C^{1}H_2-{}^{14}N$	127.4 ± 0.8	J 8, L 5
	14	$^{12}C^{1}H_2-{}^{14}N$	125.81 ± 0.23	M 8
	14	$^{12}C^{1}H_2-{}^{14}N$	125.7 ± 0.6	A 5
	14	$^{12}C^{1}H_2-{}^{14}N$	125.6 ± 0.15	J 11
Control doublets for ^{14}N, ^{1}H, ^{12}C	15	$^{12}C^{1}H_3-{}^{14}N^{1}H$	125.63 ± 0.27	M 8
	16	$^{14}N^{1}H_2-{}^{16}O$	236.9 ± 1.5	J 8, L 5
	16	$^{14}N^{1}H_2-{}^{16}O$	237.80 ± 0.32	M 8
	17	$^{14}N^{1}H_3-{}^{16}O^{1}H$	236.61 ± 0.39	M 8
	28	$^{14}N_2-{}^{12}C^{16}O$	111.7 ± 2.0	J 8, L 5
	28	$^{14}N_2-{}^{12}C^{16}O$	112.22 ± 0.40	M 8
^{15}N	15	$^{14}N^{1}H-{}^{15}N$	107.4 ± 2	J 9, L 5
	(15	$^{12}C^{1}H_3-{}^{15}N$	238.2 ± 0.7$_5$)	M 3
^{18}O	(18	$^{16}O^{1}H_2-{}^{18}O$	125.7 ± 1.8)	M 3
	(18	$^{17}O^{1}H_2-{}^{18}O$	104.4 ± 1.8)	A 13
	(18	$^{16}O^{1}H_2-{}^{18}O$	120)	M 7
^{19}F	19	$^{16}O^{2}D^{1}H-{}^{19}F$	104.4 ± 1.8	A 13
^{20}Ne	20	$^{16}O^{2}D_2-{}^{20}Ne$	308.3 ± 4.0	A 13
	20	$^{16}O^{2}D_2-{}^{20}Ne$	306.5 ± 1.0	J 10, L 5
	20	$^{12}C^{2}D_4-{}^{20}Ne$	638.16 ± 0.50	M 8
^{21}Ne	21	$^{20}Ne^{1}H-{}^{21}Ne$	72.6 ± 2.0	J 10, L 5
^{22}Ne	11	$^{10}B^{1}H-{}^{22}Ne^{2+}$	251 ± 5.0	J 10, L 5
	11	$^{11}B-{}^{22}Ne^{2+}$	136.0 ± 1.5	J 10, L 5
^{27}Al	(27	$^{12}C_2{}^{1}H_3-{}^{27}Al$	405)	A 13
^{28}Si	28	$^{12}C^{16}O-{}^{28}Si$	172 ± 6	A 13
^{29}Si	29	$^{10}B^{19}F-{}^{29}Si$	342 ± 6	A 13
^{31}P	31	$^{12}C^{19}F-{}^{31}P$	244 ± 5	A 13
^{32}S	32	$^{16}O_2-{}^{32}S$	177 ± 3	A 13
^{35}Cl	36	$^{12}C_3-{}^{35}Cl^{1}H$	225 ± 7	A 13
	37	$^{12}C_3-{}^{35}Cl^{1}H$	246.7 ± 1.7	O 1
^{37}Cl	37	$^{12}C_3{}^{1}H-{}^{37}Cl$	412 ± 7	A 13
	37	$^{12}C_3{}^{1}H-{}^{37}Cl$	421.7 ± 0.9	O 1
	38	$^{12}C_3{}^{1}H_2-{}^{37}Cl^{1}H$	419.8 ± 1.1	O 1
		Average	420.8 ± 0.7	O 1
^{36}A	(18	$^{16}O^{1}H_2-{}^{36}A^{2+}$	271 ± 3.6)	A 13
	36	$^{12}C_3-{}^{36}A$	326 ± 7	A 13
^{40}A	20	$^{16}O^{2}D_2-{}^{40}A^{2+}$	418.9 ± 2.0	J 10, L 5
	20	$^{20}Ne-{}^{40}A^{2+}$	108.8 ± 3.0	A 13
	20	$^{20}Ne-{}^{40}A^{2+}$	113.0 ± 2.0	J 10, L 5
	20	$^{20}Ne-{}^{40}A^{2+}$	111.42 ± 0.38	M 8
	40	$^{12}C_3{}^{1}H_4-{}^{40}A$	679 ± 6	A 13
	40	$^{12}C_3{}^{1}H_4-{}^{40}A$	679.3 ± 0.7	O 1
	41	$^{12}C_3{}^{1}H_5-{}^{40}A^{1}H$	693.0 ± 2.3	O 1
^{48}Ti	16	$^{16}O-{}^{48}Ti^{3+}$	115.5 ± 1.5	D 6
	24	$^{12}C_2-{}^{48}Ti^{2+}$	244.7 ± 3.6	A 14
^{56}Fe	56	$^{12}C_4{}^{1}H_8-{}^{56}Fe$	1235 ± 17	O 1
^{58}Ni	58	$^{12}C_4{}^{1}H_{10}-{}^{58}Ni$	1371.2 ± 3.9	O 2
^{60}Ni	60	$^{12}C_5-{}^{60}Ni$	695.9 ± 3.1	O 2
^{61}Ni	61	$^{12}C_5{}^{1}H-{}^{61}Ni$	735 ± 15	O 2
^{62}Ni	62	$^{12}C_5{}^{1}H_2-{}^{62}Ni$	860.7 ± 3.7	O 2
^{64}Ni	64	$^{12}C_5{}^{1}H_4-{}^{64}Ni$	1044.8 ± 5.4	O 2

	A	Doublet	$\Delta M/A = f_1 - f_2$ 10^{-4} MU	Lit.
^{48}Ti	16	$^{16}O-{}^{48}Ti^{3+}$	7.22 ± 0.1	D 6
	24	$^{12}C_2-{}^{48}Ti^{2+}$	10.20 ± 0.15	A 14
	12	$^{12}C-{}^{48}Ti^{4+}$	9.8 ± 0.4	D 6
^{52}Cr	52	$^{12}C^{1}H_3{}^{37}Cl-{}^{52}Cr$	9.22 ± 0.15	A 14
^{56}Fe	14	$^{14}N-{}^{56}Fe^{4+}$	12.3 ± 0.4	D 6
^{78}Kr	39	$^{12}C_3{}^{1}H_3-{}^{78}Kr^{2+}$	16.28 ± 0.2	A 13
^{82}Kr	41	$^{12}C_3{}^{1}H_5-{}^{82}Kr^{2+}$	20.20 ± 0.15	A 13
^{84}Kr	42	$^{12}C_3{}^{1}H_6-{}^{84}Kr^{2+}$	21.73 ± 0.15	A 13
^{86}Kr	43	$^{12}C_3{}^{1}H_7-{}^{86}Kr^{2+}$	23.10 ± 0.15	A 13
^{86}Sr	(86	$^{29}Si^{19}F_3-{}^{86}Sr$	9.0)	M 4
^{87}Sr	(87	$^{30}Si^{19}F_3-{}^{87}Sr$	8.5)	M 4
^{94}Mo	94	$^{188}Os^{2+}-{}^{94}Mo$	7.78 ± 0.3	D 6
^{95}Mo	95	$^{190}Os^{2+}-{}^{95}Mo$	7.76 ± 0.3	D 6
^{96}Mo	96	$^{192}Os^{2+}-{}^{96}Mo$	7.58 ± 0.3	D 6
	96	$^{192}Pt^{2+}-{}^{96}Mo$	8.3 ± 0.3	D 6
^{97}Mo	97	$^{194}Pt^{2+}-{}^{97}Mo$	7.7 ± 0.2	D 6
^{98}Mo	98	$^{196}Pt^{2+}-{}^{98}Mo$	7.68 ± 0.2	D 6
^{103}Rh	103	$^{206}Pb^{2+}-{}^{103}Rh$	7.96 ± 0.15	D 6
^{129}X	43	$^{12}C_3{}^{1}H_7-{}^{129}Xe$	20.16 ± 0.1	A 13
^{150}Nd	50	$^{150}Nd^{3+}-{}^{50}Ti$	5.16 ± 0.1	D 8
^{156}Gd	52	$^{156}Gd^{3+}-{}^{52}Cr$	6.37 ± 0.11	G 5
^{192}Os	96	$^{192}Os^{2+}-{}^{96}Ru$	7.91 ± 0.2	D 6
	96	$^{192}Os^{2+}-{}^{96}Ru$	7.65 ± 0.14	G 5
^{195}Pt	65	$^{195}Pt^{3+}-{}^{65}Cu$	8.93 ± 0.1	D 6
^{198}Pt	99	$^{198}Pt^{2+}-{}^{99}Ru$	8.26 ± 0.2	D 6
	99	$^{198}Pt^{2+}-{}^{99}Ru$	7.92 ± 0.10	G 5
^{204}Pb	102	$^{204}Pb^{2+}-{}^{102}Pd$	8.07 ± 0.2	D 6
^{208}Pb	104	$^{208}Pb^{2+}-{}^{104}Pd$	7.96 ± 0.15	D 6
^{232}Th	116	$^{232}Th^{2+}-{}^{116}Sn$	10.14 ± 0.1	D 6
^{238}U	119	$^{238}U^{2+}-{}^{119}Sn$	10.41 ± 0.1	D 6
	119	$^{238}U^{2+}-{}^{119}Sn$	10.12 ± 0.09	G 5
	86	$^{172}Yb^{2+}-{}^{86}Sr$	6.20 ± 0.15	G 5
	87	$^{174}Yb^{2+}-{}^{87}Sr$	6.18 ± 0.14	G 5
	91	$^{182}W^{2+}-{}^{91}Zr$	7.85 ± 0.2	D 6
	92	$^{184}W^{2+}-{}^{92}Zr$	8.05 ± 0.2	D 6

	A	Bracketing	$\Delta M/A = f_1 - \overline{f_2}$ 10^{-4} MU	Lit.
^{39}K	$19^1/_2$	$^{39}K^{2+}-\overline{^{96,99}Ru^{5+}}$	− 0.4 ± 0.3	D 6
$^{39,50}Ti$	$49^1/_4$	$^{197}Au^{2+}-\overline{^{49,50}Ti}$	+ 9.36 ± 0.2	D 6
^{54}Fe	54	$^{54}Fe-\overline{^{107,109}Ag^{2+}}$	− 2.55 ± 0.3	D 6
^{60}Ni	20	$^{60}Ni^{3+}-\overline{^{99,101}Ru^{5+}}$	− 1.1 ± 0.3	D 6
$\overline{^{63,65}Cu}$	16	$^{16}O-\overline{^{63,65}Cu^{4+}}$	− 6.9 ± 0.2	D 6
^{64}Zn	$21^1/_3$	$^{64}Zn^{3+}-\overline{^{107,109}Ag^{3+}}$	− 2.0 ± 0.3	D 6
^{66}Zn	22	$^{66}Zn^{3+}-\overline{^{109,107}Ag^{3+}}$	− 2.5 ± 0.3	D 6
$\overline{^{68,70}Zn}$	23	$^{23}Na-\overline{^{68,70}Zn^{3+}}$	+ 4.9 ± 0.5	D 6
^{69}Ga	69	$^{69}Ga-\overline{^{104,102}Pd^{3/2+1}}$)	− 1.29 ± 0.3	D 6
^{71}Ga	71	$^{71}Ga-\overline{^{106,108}Pd^{3/2+1}}$)	− 1.37 ± 0.3	D 6
$\overline{^{97,100}Mo}$	$98^1/_2$	$^{197}Au^{2+}-\overline{^{97,100}Mo}$	+ 7.95 ± 0.06	G 5
$\overline{^{98,100}Mo}$	$98^1/_2$	$^{197}Au^{2+}-\overline{^{98,100}Mo}$	+ 8.13 ± 0.07	G 5
$\overline{^{96,99}Ru}$	$97^1/_2$	$^{195}Pt^{2+}-\overline{^{96,99}Ru}$	+ 7.71 ± 0.20	G 5
$\overline{^{106,110}Pd}$	27	$^{27}Al-\overline{^{108,110}Pd^{4+}}$	+ 1.6 ± 0.3	D 6
$\overline{^{107,109}Ag}$	27	$^{27}Al-\overline{^{107,109}Ag^{4+}}$	+ 1.2 ± 0.2	D 6
$\overline{^{116,118}Sn}$	$23^1/_2$	$^{47}Ti^{2+}-\overline{^{118,116}Sn^{5+}}$	− 2.23 ± 0.4	D 8
$\overline{^{118,119}Sn}$	$39^2/_5$	$^{197}Au^{5+}-\overline{^{118,119}Sn^{3+}}$	+ 7.2 ± 0.3	D 8
$\overline{^{122,124}Sn}$	$24^1/_2$	$^{49}Ti^{2+}-\overline{^{122,124}Sn^{5+}}$	− 2.73 ± 0.4	D 8
^{139}La	$46^1/_3$	$^{139}La^{3+}-\overline{^{46,47}Ti}$	+ 3.97 ± 0.2	D 8
$\overline{^{146,048}Nd}$	49	$^{49}Ti-\overline{^{46,1148}Nd^{3+}}$	− 4.60 ± 0.1	D 8

[1]) Pd ions which are ionized 6 times when they pass the electrical deflecting field of the mass spectrograph and which capture 3 electronic charges before they enter the magnetic field. With respect to their mass, they behave as $3^2/_6 = 3/_2$-times charged ions.

	A	Bracketing	$\Delta M/A = f_1 - \bar{f}_2$ 10^{-4} MU	Lit.		A	Bracketing	$\Delta M/A = f_1 - \bar{f}_2$ 10^{-4} MU	Lit.
^{148}Nd	$49^1/_3$	$^{148}Nd^{3+} - \overline{^{49,50}Ti}$	+ 4.79 ± 0.1	D 8	$\overline{^{203,205}Tl}$	102	$^{102}Pd - \overline{^{203,205}Tl^{2+}}$	− 8.03 ± 0.2	D 6
$\overline{^{155,157}Gd}$	52	$^{52}Cr - \overline{^{155,157}Gd^{3+}}$	− 6.39 ± 0.09	G 5	^{209}Bi	$104^1/_2$	$^{209}Bi^{2+} - \overline{^{104,105}Pd}$	+ 7.84 ± 0.1	D 6
$\overline{^{158,160}Gd}$	53	$^{53}Cr - \overline{^{158,160}Gd^{3+}}$	− 6.38 ± 0.13	G 5	^{235}U	$117^1/_2$	$^{235}U^{2+} - \overline{^{117,118}Sn}$	+ 10.5 ± 0.3	D 6
^{160}Gd	$53^1/_3$	$^{160}Gd^{3+} - \overline{^{53,54}Cr}$	+ 6.33 ± 0.26	G 5	^{238}U	119	$^{238}U^{2+} - \overline{^{118,120}Sn}$	+ 10.12 ± 0.13	G 5
^{190}Os	96	$^{96}Ru - \overline{^{190}Os^{2+}, ^{194}Pt^{2+}}$	− 7.70 ± 0.11	G 5		86	$^{86}Sr - \overline{^{171,173}Yb^{2+}}$	− 6.48 ± 0.19	G 5
^{191}Ir	$95^1/_2$	$^{191}Ir^{2+} - \overline{^{95,96}Mo}$	+ 7.68 ± 0.2	D 6		87	$^{87}Sr - \overline{^{173}Yb^{2+}, ^{175}Cp^{2+}}$	− 6.37 ± 0.16	G 5
$\overline{^{191,193}Ir}$	96	$^{96}Mo - \overline{^{191,193}Ir^{2+}}$	− 7.72 ± 0.2	D 6		$90^1/_2$	$^{181}Ta^{2+} - \overline{^{90,91}Zr}$	+ 7.71 ± 0.09	G 5
^{194}Pt	97	$^{194}Pt^{2+} - \overline{^{96,99}Ru}$	+ 7.72 ± 0.17	G 5		$90^1/_2$	$^{181}Ta^{2+} - \overline{^{90,92}Zr}$	+ 7.77 ± 0.08	G 5
^{196}Pt	98	$^{196}Pt^{2+} - \overline{^{99,96}Ru}$	+ 7.69 ± 0.20	G 5		174	$^{174}Yb - \overline{^{173}Yb, ^{175}Cp}$	+ 0.05 ± 0.20	G 5
^{197}Au	$65^2/_3$	$^{197}Au^{3+} - \overline{^{65,63}Cu}$	+ 8.90 ± 0.2	D 6		175	$^{175}Cp - \overline{^{176,173}Yb}$	+ 0.00 ± 0.34	G 5

Literature

for Tables I - III

(1) Alvarez, L. W. & R. Cornog: Physic. Rev. **56** (1939) 379, 613.
(2) Alvarez, L. W. & F. Bloch: Physic. Rev. **57** (1940) 111.
(3) Anderson, O. E.: Physic. Rev. **45** (1934) 685.
(4) Anderson, O. E.: Physic. Rev. **46** (1934) 473.
(5) Asada, T., T. Okuda, K. Ogata & S. Yoshimoto: Nature, London **143** (1939) 797. Proc. physic.-math. Soc. Japan (3) **22** (1940) 41.
(5a) Ashley, M.: Physic. Rev. **44** (1933) 919.
(6) Aston, F. W.: Phil. Mag. J. Sci. **47** (1924) 385.
(7) Aston, F. W.: Proc. roy. Soc. London (A) **130** (1931) 302.
(8) Aston, F. W.: Proc. roy. Soc. London (A) **132** (1931) 487.
(9) Aston, F. W.: Mass-Spectra and Isotopes, London 1933.
(10) Aston, F. W.: Proc. roy. Soc. London (A) **146** (1934) 46.
(11) Aston, F. W.: Proc. roy. Soc. London (A) **149** (1935) 396.
(12) Aston, F. W.: Nature, London **137** (1936) 613.
(13) Aston, F. W.: Proc. roy. Soc. London (A) **163** (1937) 391.
(14) Aston, F. W.: Nature, London **141** (1938) 1096.

(1) Bacher, R. F. & D. H. Tomboulian: Physic. Rev. **50** (1936) 1096; **52** (1937) 836.
(2) Back, E. & S. Goudsmit: Z. Physik **47** (1928) 174.
(3) Badami, J. S.: Z. Physik **79** (1932) 206, 224.
(4) Bainbridge, K. T.: Physic. Rev. **39** (1932) 1021.
(5) Bainbridge, K. T.: Physic. Rev. **43** (1933) 1056.
(6) Bainbridge, K. T.: J. Franklin Inst. **215** (1933) 509.
(7) Bainbridge, K. T. & E. B. Jordan: Physic. Rev. **49** (1936) 883.
(8) Bainbridge, K. T. & E. B. Jordan: Physic. Rev. **50** (1936) 282.
(9) Bainbridge, K. T. & E. B. Jordan: Physic. Rev. **51** (1937) 384.
(10) Bainbridge, K. T.: Physic. Rev. **53** (1938) 922.
(11) Ballard, S. S.: Physic. Rev. **46** (1934) 806.
(12) Benson, A. N. & R. A. Sawyer: Physic. Rev. **52** (1937) 1127.
(13) Bethe, H. A. & R. F. Bacher: Rev. mod. Physic. **8** (1936) 82.
(14) Bleakney, W.: Physic. Rev. **43** (1933) 1056.
(15) Bleakney, W., G. P. Harnwell, W. W. Lozier, P. T. Smith & H. D. Smyth: Physic. Rev. **46** (1934) 81.
(16) Blewett, J. P. & M. B. Sampson: Physic. Rev. **49** (1936) 778.
(17) Blewett, J. P.: Physic. Rev. **49** (1936) 900.
(18) Brewer, A. K.: Physic. Rev. **47** (1935) 571.
(19) Brewer, A. K.: J. Amer. chem. Soc. **58** (1936) 370.
(20) Brewer, A. K.: Physic. Rev. **49** (1936) 56.

(1) Campbell, J. S.: Z. Physik **84** (1933) 393.
(2) Campbell, J. S.: Nature, London **131** (1933) 204.
(3) Casimir, H.: Physica **2** (1935) 719.
(4) Cohen, V. W.: Physic. Rev. **46** (1934) 713.
(5) Crawford, M. F. & A. M. Crooker: Nature, London **131** (1933) 655.
(6) Crawford, M. F. & S. Bateson: Canad. J. Res. **10** (1934) 693.
(7) Crawford, M. F. & N. S. Grace: Physic. Rev. **47** (1935) 536.
(8) Crawford, M. F.: Physic. Rev. **47** (1935) 768.

(1) Dempster, A. J.: Physic. Rev. **17** (1921) 427; **18** (1921) 415. Proc. Amer. Nat. Acad. **7** (1921) 45.
(2) Dempster, A. J.: Proc. Amer. Nat. Acad. **75** (1935) 755. Nature, London **136** (1935) 65.
(3) Dempster, A. J.: Physic. Rev. **49** (1936) 947.
(4) Dempster, A. J.: Physic. Rev. **50** (1936) 186.
(5) Dempster, A. J.: Physic. Rev. **52** (1937) 1074.
(6) Dempster, A. J.: Physic. Rev. **53** (1938) 64.
(7) Dempster, A. J.: Physic. Rev. **53** (1938) 727.
(8) Dempster, A. J.: Physic. Rev. **53** (1938) 869.
(9) Dempster, A. J.: Physic. Rev. **55** (1939) 794.

(1) Ellett, A. & N. P. Heydenburg: Physic. Rev. **46** (1934) 583.
(2) Elliot, A.: Proc. roy. Soc. London (A) **127** (1930) 638.

(1) Fisher, R. A. & E. R. Peck: Physic. Rev. **55** (1939) 270.
(2) Fox, M. & I. I. Rabi: Physic. Rev. **48** (1935) 746.
(3) Frisch, O. R., H. v. Halban jr. & J. Koch: Physic. Rev. **53** (1938) 719. Nature, London **139** (1937) 756, 1021; **140** (1937) 360.
(4) Fuchs, B. & H. Kopfermann: Naturwiss. **23** (1935) 372.

(1) Gale, H. G. & G. S. Monk: Astrophysic. J. **69** (1929) 77.
(2) Gier, J. de & P. Zeeman: Kon. Akad. Wetensch. Amsterdam **38** (1935) 810.
(3) Gollnow, H.: Z. Physik **103** (1936) 443.
(4) Granath, L. P. & C. M. Van Atta: Physic. Rev. **44** (1933) 935.
(5) Graves, A. C.: Physic. Rev. **55** (1939) 863.
(6) Gremmer, W. & R. Ritschl: Z. Instr.-Kd. **51** (1931) 170.
(7) Güttinger, P.: Z. Physik **64** (1930) 749.

(1) Hahn, O., F. Straßmann & E. Walling: Naturwiss. **25** (1937) 189.
(2) Hardy, T. C.: Physic. Rev. **59** (1941) 686 (abs. 20).

(3) Harvey, A. & F. A. Jenkins: Physic. Rev. **35** (1930) 789.
(4) Hay, R. H.: Physic. Rev. **58** (1940) 180.
(5) Hay, R. H.: Physic. Rev. **59** (1941) 686 (abs. 19).
(6) Hemmendinger, A. & W. R. Smythe: Physic. Rev. **51** (1937) 1052.
(7) Hevesy, G. v.: Naturwiss. **35** (1935) 583.
(8) Heyden, M. & H. Kopfermann: Z. Physik **108** (1938) 232.
(9) Heyden, M. & R. Ritschl: Z. Physik **108** (1938) 739.
(10) Heyden, M. & W. Wefelmeier: Naturwiss. **26** (1938) 612.
(11) Hönigschmid, O. & F. Hirschbold-Wittner: Z. anorg. allg. Chem. **243** (1940) 355.
(12) Hönigschmid, O. & F. Hirschbold-Wittner: Z. anorg. allg. Chem. **244** (1940) 63.
(13) Hoffman, J. G., M. St. Livingston & H. A. Bethe: Physic. Rev. **51** (1937) 214.
(14) Hori, T.: Z. Physik **44** (1927) 834.

(1) Inglis, D. R.: Physic. Rev. **58** (1940) 577.

(1) Jackson, D. A.: Z. Physik **75** (1932) 229
(2) Jackson, D. A.: Proc. roy. Soc. London (A) **139** (1933) 673.
(3) Jackson, D. A.: Z. Physik **80** (1933) 59.
(4) Jackson, D. A. & H. Kuhn: Proc. roy. Soc. London (A) **158** (1937) 372.
(4a) Jackson, D. A. & H. Kuhn: Proc. roy. Soc. London (A) **173** (1939) 278.
(5) Jaeckel, B.: Z. Physik **100** (1936) 513.
(5a) Jenkins, F. A. & M. Ashley: Physic. Rev. **39** (1932) 552.
(6) Jones, E. G.: Proc. physic. Soc. London **45** (1938) 625.
(7) Jones, E. G.: Proc. roy. Soc. London (A) **144** (1934) 587.
(8) Jordan, E. B. & K. T. Bainbridge: Physic. Rev. **49** (1936) 883.
(9) Jordan, E. B. & K. T. Bainbridge: Physic. Rev. **50** (1936) 98.
(10) Jordan, E. B. & K. T. Bainbridge: Physic. Rev. **51** (1937) 385.
(11) Jordan, E. B.: Physic. Rev. **58** (1940) 1009.

(1) Kapuscinski, W. & J. G. Eymers: Proc. roy. Soc. London (A) **122** (1929) 58.
(2) Kellogg, J. M. B., I. I. Rabi, N. F. Ramsey jr. & J. R. Zacharias: Physic. Rev. **55** (1939) 318; **57** (1940) 677.
(3) Kellogg, J. M. B., I. I. Rabi, N. F. Ramsey jr. & J. R. Zacharias: Physic. Rev. **56** (1939) 728.
(4) Kopfermann, H.: Z. Physik **73** (1931) 437.
(5) Kopfermann, H.: Z. Physik **75** (1932) 363.
(6) Kopfermann, H.: Z. Physik **83** (1933) 417.
(7) Kopfermann, H. & E. Rindal: Z. Physik **87** (1934) 460.
(8) Kopfermann, H. & E. Rasmussen: Z. Physik **92** (1934) 82.
(9) Kopfermann, H. & E. Rasmussen: Naturwiss. **22** (1934) 291. Z. Physik **94** (1935) 58.
(10) Kopfermann, H. & E. Rasmussen: Z. Physik **98** (1936) 624.
(11) Kopfermann, H. & H. Wittke: Z. Physik **105** (1937) 16.
(12) Korsching, H.: Z. Physik **109** (1938) 349.
(13) Krüger, H.: Z. Physik **111** (1939) 467.
(14) Kusch, P., S. Millman & I. I. Rabi: Physic. Rev. **55** (1939) 666.
(15) Kusch, P., S. Millman & I. I. Rabi: Physic. Rev. **55** (1939) 1176.
(16) Kusch, P. & S. Millman: Physic. Rev. **56** (1939) 527.

(1) Larrich, L.: Physic. Rev. **46** (1934) 581.
(2) Lichtblau, H.: Naturwiss. **27** (1939) 260.
(3) Lichtblau, H. & J. Mattauch: Z. Physik **117** (1941) 502.
(4) Libby, W. F.: Physic. Rev. **56** (1939) 21.
(5) Livingston, M. St. & H. A. Bethe: Rev. mod. Physic. **9** (1937) 245.
(6) Lyshede, J. M. & E. Rasmussen: Z. Physik **104** (1937) 434.

(1) Manley, J. H.: Physic. Rev. **49** (1936) 921.
(2) Manley, J. H. & S. Millman: Physic. Rev. **51** (1937) 19.
(3) Mattauch, J.: S. B. Akad. Wiss. Wien **145** (1936) 461. Physic. Rev. **50** (1936) 617.
(4) Mattauch, J.: Naturwiss. **25** (1937) 170.
(4a) Mattauch, J.: Naturwiss. **25** (1937) 189.
(5) Mattauch, J. & R. Herzog: Naturwiss. **25** (1937) 747.
(6) Mattauch, J. & V. Hauk: Naturwiss. **25** (1937) 780.
(7) Mattauch, J.: Physikal. Z. **38** (1937) 951.
(8) Mattauch, J.: Physikal. Z. **39** (1938) 892.
(9) Mattauch, J. & H. Lichtblau: Z. Physik **111** (1939) 514.
(10) Mattauch, J. & H. Lichtblau: Z. physik. Chem. B **42** (1939) 288.
(11) McKellar, A.: Physic. Rev. 45 (1934) 761.
(12) McLennan, J. C. & E. J. Allin: Proc. roy. Soc. London (A) **129** (1930) 43.
(13) McLennan, J. C. & M. F. Crawford: Proc. roy. Soc. London (A) **132** (1931) 10.
(14) McLennan, J. C., M. F. Crawford & L. B. Leppard: Nature, London **128** (1931) 301.
(15) McMillan, E. & N. S. Grace: Physic. Rev. **44** (1933) 949.
(16) Meggers, W. F.: Physic. Rev. **37** (1931) 219.
(17) Meggers, W. F., A. S. King & R. F. Bacher: Physic. Rev. **38** (1931) 1258.
(18) Millman, S.: Physic. Rev. **47** (1935) 739.
(19) Millman, S. & M. Fox: Physic. Rev. **50** (1936) 220.
(20) Millman, S., I. I. Rabi & J. R. Zacharias: Physic. Rev. **53** (1938) 384.
(21) Millman, S., P. Kusch & I. I. Rabi: Physic. Rev. **54** (1938) 968.
(22) Millman, S.: Physic. Rev. **55** (1939) 628.
(23) Millman, S., P. Kusch & I. I. Rabi: Physic. Rev. **56** (1939) 165.
(24) Millman, S. & P. Kusch: Physic. Rev. **56** (1939) 303.
(25) More, K. R.: Physic. Rev. **46** (1934) 470.
(25a) Mrozowski, S.: Physic. Rev. **57** (1940) 207.
(26) Murakawa, K.: Z. Physik **109** (1938) 162.
(27) Murakawa, K.: Z. Physik **112** (1939) 234; **114** (1939) 651.
(28) Murphey, B. F.: Physic. Rev. **59** (1941) 320.
(29) Murphey, B. F. & A. O. Nier: Physic. Rev. **59** (1941) 771.
(30) Murphy, G. M. & H. Johnston: Physic. Rev. **46** (1934) 95.

(1) Nier, A. O.: Physic. Rev. **48** (1935) 283.
(2) Nier, A. O.: Physic. Rev. **49** (1936) 272.
(3) Nier, A. O. & E. E. Hanson: Physic. Rev. **50** (1936) 722.
(4) Nier, A. O.: Physic. Rev. **48** (1935) 283; **50** (1936) 1041.
(5) Nier, A. O.: Physic. Rev. **51** (1937) 1007.
(6) Nier, A. O.: Physic. Rev. **52** (1937) 885.
(7) Nier, A. O.: Physic. Rev. **52** (1937) 933.
(8) Nier, A. O.: Physic. Rev. **53** (1938) 282.
(9) Nier, A. O.: Physic. Rev. **54** (1938) 275.
(10) Nier, A. O.: J. Amer. chem. Soc. **60** (1938) 1571.
(11) Nier, A. O.: Physic. Rev. **55** (1939) 150.
(12) Nier, A. O.: Physic. Rev. **55** (1939) 1143.

(1) Okuda, T., K. Ogata, K. Aoki & Y. Sugawara: Physic. Rev. **58** (1940) 578.
(2) Okuda, T., K. Ogata, H. Kuroda, S. Shima & S. Shindo: Physic. Rev. **59** (1941) 104.
(3) Ornstein, L. S. & W. R. van Wijk: Z. Physik **49** (1928) 315.

(1) Paschen, F. & J. S. Campbell: Naturwiss. **22** (1934) 136.
(2) Perey, Mlle M.: C. R. Séances Acad. Sci. Paris **208** (1939) 97. J. Physiq. Radium **10** (1939) 435.
(3) Perey, Mlle M. & M. M. Lecoin: J. Physiq. Radium **10** (1939) 439.
(4) Powers, P. N., H. Carrol, H. Bayer & J. R. Dunning: Physic. Rev. **51** (1937) 51, 371, 1112; **52** (1937) 38.

(1) Rabi, I. I. & V. W. Cohen: Physic. Rev. **46** (1934) 707.
(2) Rabi, I. I., S. Millman, P. Kusch & J. R. Zacharias: Physic. Rev. **53** (1938) 495.
(3) Rabi, I. I., S. Millman, P. Kusch & J. R. Zacharias: Physic. Rev. **55** (1939) 526.
(4) Rasmussen, E.: Naturwiss. **23** (1935) 69.
(5) Rasmussen, E.: Z. Physik **104** (1936) 229.
(5a) Renzetti, N. A.: Physic. Rev. **57** (1940) 753.
(6) Ritschl, R.: Naturwiss. **19** (1931) 690.
(7) Ritschl, R.: Z. Physik **79** (1932) 1.
(8) Rose, J. L.: Physic. Rev. **47** (1935) 122.

(1) Sampson, M. B. & W. Bleakney: Physic. Rev. **50** (1936) 456.
(2) Sampson, M. B. & W. Bleakney: Physic. Rev. **50** (1936) 732.
(3) Schmidt, Th.: Z. Physik **101** (1936) 486.
(4) Schmidt, Th.: Z. Physik **108** (1938) 408.
(5) Schmidt, Th.: Z. Physik **112** (1939) 199.
(6) Schmidt, Th.: Z. Physik **113** (1939) 140.
(6a) Schmidt, Th.: Naturwiss. **28** (1940) 565.
(7) Schüler, H. & H. Brück: Z. Physik **56** (1929) 291.
(8) Schüler, H.: Z. Physik **66** (1930) 431.
(9) Schüler, H. & J. E. Keyston: Z. Physik **67** (1931) 433; **71** (1931) 413.
(10) Schüler, H. & J. E. Keyston: Z. Physik **70** (1931) 1.
(11) Schüler, H. & J. E. Keyston: Z. Physik **72** (1931) 423.
(12) Schüler, H. & E. G. Jones: Z. Physik **74** (1932) 631.
(13) Schüler, H. & H. Westmeyer: Z. Physik **82** (1933) 685.
(14) Schüler, H. & H. Westmeyer: Naturwiss. **21** (1933) 660.
(15) Schüler, H. & H. Gollnow: Naturwiss. **22** (1934) 511.
(16) Schüler, H. & H. Gollnow: Naturwiss. **22** (1934) 730.
(17) Schüler, H. & Th. Schmidt: Naturwiss. **22** (1934) 758.
(18) Schüler, H. & Th. Schmidt: Naturwiss. **22** (1934) 838.
(19) Schüler, H.: Z. Physik **88** (1934) 323.
(20) Schüler, H. & Th. Schmidt: Z. Physik **94** (1935) 457.
(21) Schüler, H. & Th. Schmidt: Naturwiss. **23** (1935) 69.
(22) Schüler, H. & Th. Schmidt: Z. Physik **95** (1935) 265.
(23) Schüler, H. & Th. Schmidt: Z. Physik **98** (1935) 239.
(24) Schüler, H. & Th. Schmidt: Z. Physik **99** (1936) 717.
(25) Schüler, H. & Th. Schmidt: Z. Physik **100** (1936) 113.
(26) Schüler, H. & M. Marketu: Z. Physik **102** (1936) 703.
(27) Schüler, H. & H. Korsching: Z. Physik **103** (1936) 434.
(28) Schüler, H. & Th. Schmidt: Z. Physik **104** (1937) 468.
(29) Schüler, H. & H. Korsching: Z. Physik **105** (1937) 168.
(30) Schüler, H., J. Roig & H. Korsching: Z. Physik **111** (1938) 165.
(31) Schüler, H. & H. Korsching: Z. Physik **111** (1938) 386.
(32) Schüler, H. & H. Gollnow: Z. Physik **113** (1939) 1.
(33) Sherr, R., L. G. Smith & W. Bleakney: Physic. Rev. **54** (1938) 388.
(33a) Shrader, E. F.: Physic. Rev. **58** (1940) 475. — Shrader, E. F., S. Millman & P. Kusch: Physic. Rev. **58** (1940) 925.
(34) Smythe, W. R.: Physic. Rev. **45** (1934) 299.
(35) Smythe, W. R. & A. Hemmendinger: Physic. Rev. **51** (1937) 178.
(36) Straus, H. A.: Physic. Rev. **59** (1941) 102, 430.
(37) Swartout, J. A. & M. Dole: J. Amer. chem. Soc. **61** (1939) 2025.

(1) Tolansky, S.: Proc. roy. Soc. London (A) **136** (1932) 585.
(2) Tolansky, S.: Proc. roy. Soc. London (A) **137** (1932) 541.
(3) Tolansky, S.: Proc. roy. Soc. London (A) **144** (1934) 574.
(4) Tolansky, S.: Proc. roy. Soc. London (A) **146** (1934) 182.
(5) Tolansky, S.: Proc. roy. Soc. London (A) **149** (1935) 262; **152** (1935) 663. Proc. physic. Soc. London **48** (1936) 49. — Tolansky, S. & G. O. Forester: Proc. roy. Soc. London (A) **168** (1938) 78.
(6) Tolansky, S. & E. Lee: Proc. roy. Soc. London (A) **158** (1937) 110.
(7) Tomboulian, D. H. & R. F. Bacher: Physic. Rev. **58** (1940) 52.
(8) Townes, C. H. & W. R. Smythe: Physic. Rev. **56** (1939) 1210.

(1) Valley, G. E.: Physic. Rev. **57** (1940) 945 (abs. 22).
(2) Valley, G. E. & H. H. Anderson: Physic. Rev. **59** (1941) 113 (abs. 41).
(3) Valley, G. E.: Physic. Rev. **59** (1941) 836.
(4) Venkatesaschar, B. & L. Sibaiya: Nature, London **136** (1935) 65. Proc. Indian Acad. Sci. (A) **1** (1935) 955; **2** (1935) 101.
(5) Venkatesaschar, B. & L. Sibaiya: Nature, London **136** (1935) 437. Proc. Indian Acad. Sci. (A) **2** (1935) 203.
(6) Vaughan, A. L., J. H. Williams & J. T. Tate: Physic. Rev. **46** (1934) 327.

(1) Wahl, W.: Naturwiss. **29**, (1941) 536.
(1a) White, H. E.: Physic. Rev. **34** (1929) 1397.
(2) White, H. E. & R. Ritschl: Physic. Rev. **35** (1930) 1146.
(2a) Wilkins, T. R. & A. J. Dempster: Physic. Rev. **54** (1938) 315.
(3) Wood, R. W. & G. H. Dieke: J. chem. Physics **6** (1938) 908; **8** (1940) 351.
(4) Wulff, J.: Physic. Rev. **44** (1933) 512.
(5) Wurm, K.: Naturwiss. **20** (1932) 85.

(1) Zacharias, J. R. & J. M. B. Kellogg: Physic. Rev. **57** (1940) 570 (abs. 74).
(2) Zeeman, P., J. H. Gisolf & T. L. de Bruin: Nature, London **128** (1931) 637.

Table IV

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
0	**n**	1	1	—	—	—	—	—	1.008945	0.025
1	**H**	**0**	**1**	99.98_8	—	—	—	—	1.008131	0.0032
	D	**1**	**2**	0.01_5	—	—	—	—	2.014725	0.0064
	T	2	3	—	$[31 \pm 8]\ a$	β^-	0.015 ± 0.003; 0.013 ± 0.005; 0.0095 ± 0.0020;		3.017004	0.020
2	**He**	**1**	**3**	10^{-5}	—	—	—	—	3.016988	0.020
		2	**4**	~100	—	—	—	—	4.003860	0.031
		3	5	—	$\sim 6 \cdot 10^{-20}\ s$	$\alpha + n$	—	—	5.015428	—
		4	6	—	$[0.8 \pm 0.1]\ s$	β^-	3.7	—	6.0209	—
3	**Li**	**3**	**6**	7.9	—	—	—	—	6.016917	0.051
		4	**7**	92.1	—	—	—	—	7.018163	0.057
		5	8	—	$[0.9 \pm 0.1]\ s$	β^-, α	12	—	8.024967	0.066
4	**Be**	3	7	—	$[53 \pm 2]\ d$	K	—	0.425 ± 0.025	7.019089	0.066
		4	8	—	unstable $< 1\ s$	2α	—	—	8.007807	0.039
		5	**9**	100	—	—	—	—	9.014958	0.062
		6	10	—	$\sim 10^6\ a$	β^-	0.55	—	10.016622	0.136
5	**B**	4	9	—	unstable	$2\alpha + p$	—	—	9.016104	0.068
		5	**10**	20	—	—	—	—	10.016169	0.070
		6	**11**	80	—	—	—	—	11.012901	0.050
		7	12	—	$[0.022 \pm 0.002]\ s$	β^-	12	—	12.0168	—
6	**C**	4	10	—	$[8.8 \pm 0.8]\ s$	β^+	3.36 ± 0.1	—	10.02086	—
		5	11	—	$21\ m$	β^+	0.981 ± 0.005; 0.95 ± 0.03; 1.03 ± 0.03		11.015017	0.075
		6	**12**	98.9	—	—	—	—	12.003880	0.025
		7	**13**	1.1	—	—	—	—	13.007561	0.043
		(isomer)		—	?	—	—	—	—	—
		8	14	—	10^3 to $10^5\ a$	β^-	0.145 ± 0.015; 0.090 ± 0.015	none	14.007741	0.043
7	**N**	6	13	—	$[9.93 \pm 0.03]\ m$	β^+	1.218 ± 0.004; 1.198 ± 0.006; 0.92, 1.20	0.285 ± 0.010	13.009904	0.044
		7	**14**	99.62	—	—	—	—	14.007530	0.016
		8	**15**	0.38	—	—	—	—	15.004870	0.072
		9	16	—	$8.4\ s$	β^-	6.0	—	16.00645	—
8	**O**	7	15	—	$[125 \pm 5]\ s$	β^+	1.7	—	15.0078	—
		8	**16**	99.76	—	—	—	—	16.— Standard	
		9	**17**	0.04	—	—	—	—	17.00450	0.06
		10	**18**	0.20	—	—	—	—	18.00485	0.18
		11	19	—	$31\ s$	β^-	—	—	—	—

^{1}H: [25] C 10, R 8, S 52, R 21, K 11, N 22, V 3c. — ^{2}H: [21] L 24, F 18, K 8. — ^{3}H: [6] O 12; [8] O 11, O 12; L 30; B 59a; [20] O 5, D 10, O 9, N 9, A 22, B 43, H 63, H 69, A 24, B 59a, M 7a; [22] A 27, C 17, L 52, T 5, R 26, D 35, L 54, R 34. — ^{3}He: [14] O 4, O 7, N 8, R 34, A 18, P 7, M 43a, A 18a; [18] O 1, D 11, B 32, B 34, B 38, B 4, P 1, B 40b. — ^{4}He: [14] D 9, L 50, K 16, O 9, C 23, G 9, R 34, S 40, N 9, Y 6, Y 7; [19] O 4, D 9, L 28, O 6, O 9, R 34, S 40, N 9. — ^{5}He: [6] W 19; [19] W 19, S 50, R 34, S 47. — ^{6}He: [6] B 29; [8] B 27, B 29; [22] B 25, B 26, B 27, P 10, B 29; [23] K 20, V 7, N 2. — ^{6}Li: [14] D 25, K 17, O 10, A 13, D 27, A 15. — ^{7}Li: [19] O 10, M 11, F 16, A 17, G 17, S 38; [20] L 15, O 4, O 6, C 19, D 15, R 32, R 34, N 9; [22] A 28, D 35, T 4, T 5, R 26, F 27, H 31, L 54, M 11, W 20. — ^{8}Li: [6] L 29, R 33; [8] B 15; [20] C 45, D 15, L 29, R 33, B 15, R 34; [21] K 20, V 7, N 2; [22] W 1, N 2, L 14. — ^{7}Be: [6] H 55; [7] R 20; [9] R 20, M 4; [14] R 20, M 4; [16] D 29, H 53, H 54, H 25, H 55, H 56, H 27a; [18] R 32, R 20, R 34, R 31a. — ^{8}Be: [6] G 11; [14] K 15, O 10, G 11, L 1, Y 4, C 26, S 39, N 9; [15] O 8, O 10, K 18, A 16; [17] T 10, L 12, R 32, G 3, D 16, G 6, C 58, H 67; [18] B 31, K 5, R 7a; [19] C 18, Y 4, S 39, B 18c; [21] O 10, M 22, L 30, O 11; [24] R 35; [25] B 57, S 60, C 10, M 36, G 11, C 26, N 22, S 21a. — ^{9}Be: [19] C 23; [22] F 9, H 23. — ^{10}Be: [6] C 27b; [8] C 27b; [20] O 8, O 10, P 20; [23] M 11, F 16, B 58a. — ^{9}B: [6] H 55, H 26; [16] H 54, H 55, H 26, H 56, H 27a. — ^{10}B: [13] B 44, C 52; [17] C 43, C 47, C 57; [18] C 38, B 34, R 34. — ^{11}B: [19] C 24, H 63; [20] C 19, C 42, C 23, Y 4, S 39; [22] F 7, H 22, K 34, B 35, W 18, O 15, B 4, H 66, H 21a. — ^{12}B: [6] B 16; [8] B 15; [20] C 44, F 20, B 15, B 16. — ^{10}C: [6] B 7; [8] D 18a; [16] B 7, D 18a. — ^{11}C: [6] D 18a; [8] T 9a; D 18a; M 43; [14] B 5, W 16, D 18a;

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

(α, p)	(α, n)	(p, α)	(p, d)	(p, n)	(p, γ)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{1}n
—	—	—	—	—	—	—	—	—	$^{3}_{1}H$	—	—	—	$^{3}_{1}H$	^{1}H
—	—	—	—	—	—	$^{3}_{2}He$	—	$^{3}_{1}H$	$^{1}_{1}H$	—	—	—	$^{1}_{1}H$	^{2}H
—	—	—	—	—	—	—	—	$^{2}_{1}H$	—	$^{6}_{3}Li$	—	—	—	^{3}H
—	—	$^{6}_{3}Li$	—	—	—	$^{2}_{1}H$	—	—	—	—	—	—	—	^{3}He
—	—	$^{7}_{3}Li$	—	—	—	—	$^{6}_{3}Li$	—	—	—	—	—	—	^{4}He
—	—	—	—	—	—	—	$^{7}_{3}Li$	—	—	—	—	—	—	^{5}He
—	—	—	—	—	—	—	—	—	—	$^{7}_{4}Be$	($^{6}_{3}Li$)	—	—	^{6}He
—	—	$^{9}_{4}Be$ $^{3}_{2}He$	—	—	—	$^{7}_{4}Be$	$^{4}_{2}He$	$^{7}_{3}Li$	—	$^{3}_{1}H$	($^{6}_{2}He$)	—	—	^{6}Li
—	$^{10}_{5}B$	$^{4}_{2}He$	—	$^{7}_{4}Be$	$^{8}_{4}Be$	$^{8}_{4}Be$	$^{9}_{4}Be$ $^{5}_{2}He$	$^{6}_{3}Li$ $^{8}_{3}Li$	($^{8}_{3}Li$)	$^{10}_{5}B$	—	—	—	^{7}Li
—	—	—	—	—	—	—	—	$^{7}_{3}Li$	($^{7}_{3}Li$)	$^{11}_{5}B$	—	—	—	^{8}Li
—	—	$^{10}_{5}B$	—	$^{7}_{3}Li$	—	$^{6}_{3}Li$	—	—	(d, $^{2}_{1}H$)	—	—	—	—	^{7}Be
—	—	$^{11}_{5}B$	$^{9}_{4}Be$	—	$^{7}_{3}Li$	$^{7}_{3}Li$	$^{10}_{5}B$	—	$^{9}_{4}Be$	—	—	$^{9}_{4}Be$	$^{9}_{4}Be$	^{8}Be
—	$^{12}_{6}C$	$^{6}_{3}Li$	$^{8}_{4}Be$	$^{9}_{5}B$	$^{10}_{5}B$	$^{10}_{5}B$	$^{11}_{5}B$ $^{7}_{3}Li$	$^{10}_{4}Be$	$^{8}_{4}Be$	$^{12}_{6}C$ $^{6}_{2}He$	—	$^{8}_{4}Be$	$^{8}_{4}Be$	^{9}Be
—	—	—	—	—	—	—	—	$^{9}_{4}Be$	—	—	($^{10}_{5}B$)	—	—	^{10}Be
—	—	—	—	$^{9}_{4}Be$	—	—	—	—	—	—	—	—	—	^{9}B
$^{13}_{6}C$ $^{14}_{6}C$	$^{7}_{3}Li$ $^{13}_{7}N$ $^{14}_{7}N$	$^{7}_{4}Be$ $^{8}_{4}Be$	—	$^{10}_{6}C$ $^{11}_{6}C$	$^{9}_{4}Be$ ($^{11}_{6}C$) $^{12}_{6}C$	$^{9}_{4}Be$ $^{11}_{6}C$ $^{12}_{6}C$	$^{8}_{4}Be$ $^{13}_{6}C$ $^{9}_{4}Be$	$^{11}_{5}B$ $^{10}_{5}B$ $^{13}_{5}B$ $^{11}_{5}B$	—	$^{7}_{3}Li$ $^{14}_{7}N$ $^{8}_{3}Li$	($^{10}_{4}Be$)	—	—	^{10}B
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{11}B
—	—	—	(d, γ)	$^{10}_{5}B$	—	—	—	—	—	—	—	—	—	^{12}B
—	—	$^{14}_{7}N$	—	$^{11}_{5}B$	($^{10}_{5}B$)	$^{10}_{5}B$	—	—	—	—	—	$^{12}_{6}C$	—	^{10}C
—	$^{9}_{4}Be$ $^{15}_{6}O$	$^{15}_{7}N$	$^{14}_{7}N$	—	$^{11}_{5}B$ $^{13}_{7}N$	$^{11}_{5}B$ $^{13}_{7}N$	$^{14}_{7}N$	$^{13}_{6}C$	—	$^{9}_{4}Be$	—	$^{11}_{6}C$	—	^{11}C
$^{10}_{5}B$	—	—	—	$^{13}_{7}N$	$^{14}_{7}N$	$^{14}_{7}N$	$^{15}_{7}N$ $^{11}_{5}B$	$^{12}_{6}C$ $^{14}_{6}C$	—	$^{16}_{8}O$	—	—	—	^{12}C
$^{10}_{5}B$	—	—	—	—	—	—	—	—	—	—	—	—	—	^{13}C
$^{11}_{5}B$	—	—	—	—	—	—	—	$^{13}_{6}C$	—	—	$^{14}_{7}N$	—	—	(^{13})C*
														^{14}C
—	$^{10}_{5}B$	—	—	$^{13}_{6}C$	$^{12}_{6}C$	$^{12}_{6}C$	—	—	$^{14}_{7}N$	—	—	$^{14}_{7}N$	—	^{13}N
$^{17}_{8}O$	$^{11}_{5}B$ $^{17}_{9}F$	$^{11}_{6}C$	$^{13}_{6}C$	—	$^{13}_{6}C$ $^{15}_{8}O$	$^{13}_{6}C$ $^{15}_{8}O$	$^{16}_{8}O$ $^{12}_{6}C$	$^{15}_{7}N$	$^{13}_{7}N$	$^{11}_{5}B$	$^{14}_{6}C$	$^{13}_{7}N$	—	^{14}N
—	—	$^{16}_{8}O$ $^{13}_{6}C$	—	($^{15}_{8}O$)	—	—	$^{13}_{6}C$	$^{14}_{7}N$ $^{16}_{7}N$	—	—	—	—	—	^{15}N
—	—	—	—	—	—	—	—	$^{15}_{7}N$	—	$^{19}_{9}F$	$^{16}_{8}O$	—	—	^{16}N
—	$^{12}_{6}C$	—	—	($^{15}_{7}N$)	$^{14}_{7}N$	$^{14}_{7}N$	—	—	—	—	—	$^{16}_{8}O$	$^{16}_{8}O$	^{15}O
—	—	$^{19}_{9}F$	—	—	$^{17}_{8}F$	$^{17}_{8}F$	$^{14}_{7}N$	$^{17}_{8}O$	—	$^{13}_{6}C$	$^{16}_{7}N$	$^{15}_{8}O$	$^{15}_{8}O$	^{16}O
$^{14}_{7}N$	—	—	—	—	—	$^{18}_{9}F$	$^{19}_{9}F$	$^{16}_{8}O$	—	$^{20}_{10}Ne$	—	—	—	^{17}O
—	—	$^{15}_{7}N$	—	$^{18}_{9}F$	—	—	—	—	—	—	—	—	—	^{18}O
—	—	—	—	—	—	—	—	—	—	—	$^{19}_{9}F$	—	—	^{19}O

[16] B 5, B 7, H 26, D 18a, H 27a; [17] C 41, C 46, B 5, C 57; [18] C 40, Y 5, F 20, B 34, C 57, T 9a; [24] P 28. — ^{12}C: [13] D 34, B 19, B 20, N 5a, S 59; [14] B 65, H 62, F 22, L 13a; [17] C 46, G 6; [18] B 34, C 57; [19] L 28, L 19, C 24, H 60, H 61, G 4, H 63a. — ^{13}C: [12] R 36, B 45, M 34, P 3, B 60, M 3, B 20, S 59; [19] H 60, H 63a; [20] C 19, C 24, H 63, R 22, S 23a, S 23b, B 40a, B 18a; [22] M 27, F 8, F 9, M 28, W 18, H 21a. — ^{13})C*: [3, 4] B 50; [12] B 50. — ^{14}C: [6] R 31b; [8] R 31b; R 30, K 3; [9] R 31b; [12] M 34, L 53, P 19; [20] M 22, P 19, B 53, R 30, K 3, B 18, S 23b, R 31b, B 18a; [23] K 33, B 33, B 62, B 4, H 66, R 31b, H 21a. — ^{13}N: [6] W 12; [8] T 9a; L 56; L 56, O 13; [9] R 12, W 12a; [13] C 53, B 30, A 10, F 1, E 3, R 16, M 10, S 58, B 20; [16] B 6, H 25, H 27a; [17] H 33, C 21, C 41, C 20, H 1, A 14, C 57; [18] H 33, C 40, N 11, Y 5, B 34, C 24, F 20, K 35, R 10, N 12, B 37, R 12, L 56, R 9, W 12, K 10, O 13, W 12a, H 67, N 14, B 40, R 31a, B 18a, T 9a; [21] B 43a; [24] P 26, P 28. — ^{14}N: [13] C 6, C 54, C 7, B 30, M 10, B 20; [15] B 17; [17] D 15, R 24, C 57, L 13, L 13a; [18] B 34, B 40a, B 18a; [19] C 20, C 24. — ^{15}N: [14] B 65; [20] L 19, C 24, H 60, G 4. — ^{16}N: [6] N 2; [8] F 20; [20] F 20, H 61; [22] F 14, H 23, N 2, W 18, P 10; [23] C 13, W 18. — ^{15}O: [6] L 51, M 21; [8] F 20; [13] K 12; [16] D 28, B 6; [17] D 28, C 59; [18] L 51, M 21, F 20, N 12; [24] P 26, P 28; [25] C 13, B 53. — ^{16}O: [14] C 17, O 3, H 34, M 19, H 2, D 17, H 39, G 6, B 63, C 57, D 14, B 65, H 20, M 14, B 66, F 21, C 60, H 25, E 2, M 15, V 3b, B 16a, L 13a, S 56a, B 18b. — ^{17}O: [12] P 12, S 49, S 19, H 30, S 48, S 51, F 15, P 14; [19] L 28, B 63; [20] C 19, C 24, H 63; [22] H 23, J 1, O 15. — ^{19}O: [6] N 2; [23] B 24, A 27, N 2.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
9	**F**	8	17	—	[1.23 ± 0.1] *m*	β^+	2.1	—	17.00758	—
		9	18	—	[107 ± 4] *m*	β^+	0.7	—	18.00670	0.19
		10	**19**	100	—	—	—	—	19.00454	0.12
		11	20	—	12 *s*	β^-	5.0	2.2	20.00654	—
10	**Ne**	9	19	—	[20.3 ± 0.5] *s*	β^+	2.20	—	19.00798	—
		10	**20**	90.00	—	—	—	—	19.998895	0.061
		11	**21**	0.27	—	—	—	—	19.00002	0.2
		12	**22**	9.73	—	—	—	—	21.99858	0.30
		13	23	—	[43 ± 5] *s*	β^-	4.1 ± 0.3	—	23.00084	0.35
11	**Na**	10	21	—	[23 ± 2] *s*	β^+	—	—	—	—
		11	22	—	[3.0 ± 0.2] *a*	β^+	0.55; 0.58; 0.6 ± 0.06	1.3	22.00032	0.31
		12	**23**	100	—	—	—	—	22.99644	0.18
		13	24	—	14.8 *h*	β^-	1.37 ± 0.03; 1.43 ± 0.05; 1.36 ± 0.05	0.8, 1.5, 2.0, 3.0	23.99774	0.37
12	**Mg**	11	23	—	[11.6 ± 0.5] *s*	β^+	2.82	—	23.00055	0.35
		12	**24**	77.4	—	—	—	—	23.99300	0.38
		13	**25**	11.5	—	—	—	—	24.99462	0.46
		14	**26**	11.1	—	—	—	—	25.99012	0.3
		15	27	—	[10.0 ± 0.1] *m*	β^-	1.74 ± 0.05; 1.8; 1.96; 2.05	0.88	26.99256	0.44
13	**Al**	13	26	—	[7.0 ± 0.5] *s*	β^+	2.99; 1.8; 4.6; 1.5	—	25.99443	—
		14	**27**	100	—	—	—	—	26.99069	0.43
		15	28	—	2.3 *m*	β^-	3.3	2.3	27.99077	0.37
		16	29	—	6.7 *m*	β^-	2.5	—	28.9892	—
14	**Si**	13	27	—	4.92 *s*	β^+	3.54 ± 0.1; 3.74	—	26.99611	0.45
		14	**28**	89.6	—	—	—	—	27.98723	0.45
		15	**29**	6.2	—	—	—	—	28.98651	0.62
		16	**30**	4.2	—	—	—	—	29.98399	0.50
		17	31	—	[157.3 ± 1.3] *m*	β^-	1.8	none	30.9866	—
15	**P**	14	29	—	[4.6 ± 0.2] *s*	β^+	3.63 ± 0.07	—	28.99151	—
		15	30	—	[130.6 ± 1.5] *s*	β^+	3.5 ± 0.35; 3.0 ± 0.1	—	29.9885	—
		16	**31**	100	—	—	—	—	30.98441	0.27
		17	32	—	14.295 *d* ± 2‰	β^-	1.69; 1.72; 1.72 ± 0.03	none	31.98437	0.27
		> 16	> 31	—	12.7 *s*	β^-	—	—	—	—
16	**S**	15	31	—	[3.18 ± 0.04] *s*	β^+	3.85 ± 0.07; 3.87 ± 0.15	—	30.98965	0.28
		16	**32**	95.1	—	—	—	—	31.98252	0.26
		17	**33**	0.74	—	—	—	—	32.9819	0.3
		18	**34**	4.2	—	—	—	—	33.97981	0.37
		19	35	—	—	—	—	—	—	—
		20	**36**	0.016	—	—	— or	—	—	—
		21	37	—	[88 ± 5] *d*	β^-	0.107 ± 0.020	—	—	—

^{17}F: [6] D 28; [8] K 35; [13] D 1, W 15, E 3, H 30, K 35, R 16, P 16; [17] D 28, C 59; [18] N 11, K 35, F 20, N 12, Y 2. — ^{18}F: [6] D 28; [8] Y 2, D 8; [16] D 28, B 6; [18] Y 2, D 8, W 14a; [19] S 42; [24] P 28. — ^{20}F: [6] C 45; [8] F 20, C 61; [9] C 61; [20] H 33, C 45, F 20, B 63, B 54, C 61; [21] A 27, B 24, B 23, N 2; [22] N 2. — ^{19}Ne: [6] W 16; [8] W 16; [16] W 16. — ^{20}Ne: [18] L 16, T 12, B 39, B 18b. — ^{21}Ne: [19] L 18, M 44, [20] P 21, W 12d, P 23, S 23b. — ^{22}Ne: [12] C 5, C 8, H 30, M 12. — ^{23}Ne: [6] P 23; [8] P 23, W 12d; [20] P 21, W 12d, P 23, S 23b; [22] A 27, N 2, B 25; [23] A 27, N 2, P 10. — ^{21}Na: [6] C 48; [16] C 48; [18] P 23. — ^{22}Na: [6] L 10; [8] O 13; L 10; M 2; [9] O 13; [13] B 30, F 26, M 2; [18] L 9; [19] L 9, L 10, O 13. — ^{23}Na: [12] R 37, P 14; [19] L 28, L 53. — ^{24}Na: [6] V 4, [8] K 9; L 4; M 43; [9] K 35, R 10, R 11, K 9, C 60; [19] H 35; [20] L 17, L 18, K 35, V 4, A 25, R 11, L 21, M 44, L 4, K 9, C 60, Y 0; [21] A 27, B 24; [22] A 27, K 19, P 33, B 41, F 11; [23] A 27, B 41. — ^{22}Mg: [6] W 16; [8] W 16; [16] W 16. — ^{24}Mg: [17] H 39, G 6, C 58; [18] L 18. — ^{23}Mg: [19] L 28, M 20. — ^{26}Mg: [12] K 21, M 12, H 68a; [20] P 23a. — ^{27}Mg: [6] C 51; [8] M 43; C 51; W 17; H 35; [9] R 11; [20] H 33, H 35, R 11, C 51; [21] A 27; [23] A 27, B 41, H 54, H 56. — ^{26}Al: [6] F 25, W 16; [8] W 16; F 25; M 2; B 56; [13] C 54, F 25, S 20, M 2, B 56, [16] W 16; [17] C 58, H 58. —

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

(α, p)	(α, n)	(p, α)	($^3_2$He, p)	(p, n)	(p, γ)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	$^{16}_{7}$N	—	—	—	$^{16}_{8}$O	$^{16}_{8}$O	—	—	—	—	—	—	—	^{17}F
—	—	—	—	$^{16}_{8}$O	—	$^{17}_{8}$O	$^{20}_{10}$Ne	—	—	—	—	$^{19}_{9}$F	—	^{18}F
$^{22}_{10}$Ne	$^{22}_{11}$Na	$^{16}_{8}$O	—	$^{19}_{10}$Ne	—	$^{20}_{10}$Ne	$^{17}_{8}$O	$^{20}_{9}$F	$^{20}_{9}$F	$^{16}_{7}$N	$^{13}_{8}$O	$^{18}_{9}$F	—	^{19}F
—	—	—	—	—	—	—	—	$^{19}_{9}$F	$^{19}_{9}$F	$^{23}_{11}$Na	—	—	—	^{20}F
—	—	—	—	$^{19}_{9}$F	—	—	—	—	—	—	—	—	—	^{19}Ne
$^{23}_{11}$Na	—	—	—	—	—	$^{19}_{9}$F $^{21}_{11}$Na	$^{18}_{9}$F	$^{21}_{10}$Ne	—	$^{17}_{8}$O	—	—	—	^{20}Ne
—	—	—	—	$^{21}_{11}$Na	—	($^{22}_{11}$Na)	$^{22}_{11}$Na	$^{20}_{10}$Ne	—	—	—	—	—	^{21}Ne
$^{19}_{9}$F	—	—	—	—	—	—	—	$^{23}_{10}$Ne	—	—	—	—	—	^{22}Ne
—	—	—	—	—	—	—	—	$^{22}_{10}$Ne	—	$^{26}_{12}$Mg	$^{23}_{11}$Na	—	—	^{23}Ne
—	—	—	—	$^{21}_{10}$Ne	—	$^{20}_{10}$Ne	—	—	—	—	—	—	—	^{21}Na
—	$^{19}_{9}$F	—	—	—	—	($^{21}_{10}$Ne)	$^{24}_{12}$Mg	—	—	—	—	—	—	^{22}Na
$^{20}_{10}$Ne $^{26}_{12}$Mg	$^{26}_{13}$Al	—	—	$^{23}_{12}$Mg	$^{24}_{12}$Mg	$^{24}_{12}$Mg	$^{25}_{12}$Mg $^{21}_{10}$Ne	$^{24}_{11}$Na	$^{24}_{11}$Na	$^{20}_{9}$F	$^{23}_{10}$Ne	—	—	^{23}Na
—	—	—	—	—	—	—	$^{26}_{12}$Mg	$^{23}_{11}$Na	$^{23}_{11}$Na	$^{27}_{13}$Al	$^{24}_{12}$Mg	—	—	^{24}Na
—	—	—	—	$^{23}_{11}$Na	—	—	—	—	—	—	—	—	—	^{23}Mg
$^{27}_{13}$Al	$^{27}_{14}$Si	—	—	—	$^{23}_{11}$Na	$^{23}_{11}$Na	$^{22}_{11}$Na	—	—	—	$^{24}_{11}$Na	—	—	^{24}Mg
$^{28}_{13}$Al	—	—	—	—	$^{26}_{13}$Al	—	$^{27}_{13}$Al $^{23}_{11}$Na	$^{26}_{12}$Mg	—	—	—	—	—	^{25}Mg
$^{23}_{11}$Na $^{29}_{13}$Al	—	—	—	$^{26}_{13}$Al	$^{27}_{13}$Al	—	$^{24}_{11}$Na	$^{25}_{12}$Mg $^{27}_{12}$Mg	$^{27}_{12}$Mg	$^{23}_{10}$Ne	—	—	—	^{26}Mg
—	—	—	—	—	—	—	—	$^{26}_{12}$Mg	$^{26}_{12}$Mg	—	$^{27}_{13}$Al	—	—	^{27}Mg
—	$^{23}_{11}$Na	—	—	$^{26}_{12}$Mg	$^{25}_{12}$Mg	—	—	—	—	—	—	—	—	^{26}Al
$^{24}_{12}$Mg $^{30}_{14}$Si	$^{30}_{15}$P	—	—	$^{27}_{14}$Si	$^{26}_{12}$Mg $^{28}_{14}$Si	$^{28}_{14}$Si	$^{25}_{12}$Mg	$^{28}_{13}$Al	$^{28}_{13}$Al	$^{24}_{11}$Na	$^{27}_{12}$Mg	—	—	^{27}Al
$^{25}_{12}$Mg	—	—	—	—	—	—	—	$^{27}_{13}$Al	$^{27}_{13}$Al	$^{31}_{15}$P	$^{28}_{14}$Si	—	—	^{28}Al
$^{26}_{12}$Mg	—	—	—	—	—	—	—	—	—	—	($^{29}_{14}$Si)	—	—	^{29}Al
—	$^{24}_{12}$Mg	—	—	$^{27}_{13}$Al	—	—	—	—	—	—	—	—	—	^{27}Si
$^{31}_{15}$P	$^{31}_{16}$S	—	$^{30}_{15}$P	—	$^{27}_{13}$Al	$^{27}_{13}$Al	—	—	—	—	$^{28}_{13}$Al	—	—	^{28}Si
$^{32}_{15}$P	—	—	—	$^{29}_{15}$P	—	—	—	$^{30}_{14}$Si	—	$^{32}_{16}$S	($^{29}_{13}$Al)	—	—	^{29}Si
$^{27}_{13}$Al	—	—	—	$^{30}_{15}$P	—	—	—	$^{29}_{14}$Si $^{31}_{14}$Si	$^{31}_{14}$Si	—	—	—	—	^{30}Si
—	—	—	—	—	—	—	—	$^{30}_{14}$Si	$^{30}_{14}$Si	$^{34}_{16}$S	$^{31}_{15}$P	—	—	^{31}Si
—	—	(n, p 2n)	—	$^{29}_{14}$Si	—	—	—	—	—	—	—	—	—	^{29}P
—	$^{27}_{13}$Al	$^{32}_{16}$S	$^{28}_{14}$Si	$^{30}_{14}$Si	—	—	$^{32}_{16}$S	—	—	—	—	$^{31}_{15}$P	$^{31}_{15}$P	^{30}P
$^{28}_{14}$Si $^{34}_{16}$S	$^{34}_{17}$Cl	—	—	$^{31}_{16}$S	$^{32}_{16}$S	—	—	$^{32}_{15}$P	$^{32}_{15}$P	$^{28}_{13}$Al	$^{31}_{14}$Si	$^{30}_{15}$P	$^{30}_{15}$P	^{31}P
$^{32}_{14}$Si	—	—	(α,d) or (α, pn)	—	—	—	$^{34}_{16}$S	$^{31}_{15}$P	$^{31}_{15}$P	$^{35}_{17}$Cl	$^{32}_{16}$S	—	—	^{32}P
—	—	—	—	—	—	—	—	—	—	—	$^{34}_{16}$S	—	—	> ^{31}P
—	$^{28}_{14}$Si	—	—	$^{31}_{15}$P	—	—	—	—	—	—	—	—	—	^{31}S
$^{35}_{17}$Cl	$^{35}_{18}$A	$^{30}_{15}$P	$^{34}_{17}$Cl	—	$^{31}_{15}$P	$^{33}_{17}$Cl	$^{30}_{15}$P	$^{33}_{16}$S	—	$^{29}_{14}$Si	$^{32}_{15}$P	—	—	^{32}S
—	—	—	—	$^{33}_{17}$Cl	—	$^{34}_{17}$Cl	$^{35}_{17}$Cl	$^{32}_{16}$S	—	—	—	—	—	^{33}S
$^{31}_{15}$P	—	—	—	—	—	—	$^{32}_{15}$P	$^{33}_{16}$S	or	$^{31}_{14}$Si	—	—	—	^{34}S
—	—	—	—	—	—	—	or	$^{34}_{16}$S		or	$^{35}_{17}$Cl	—	—	^{35}S
—	—	—	—	—	—	—		$^{37}_{16}$S			—	—	—	^{36}S
—	—	—	—	—	—	—		$^{36}_{16}$S	—		$^{37}_{17}$Cl	—	—	^{37}S

^{27}Al: [12] D 33, H 29; [17] C 58, H 58. — ^{28}Al: [6] H 38; [8] C 28; [9] C 28; [12] C 55, D 33, A 9, A 10, F 2, E 4, E 1, C 14, M 32, R 16, H 38; [20] L 16, M 20, C 28; [21] A 27, F 18, B 43, S 23a; [22] A 27; [23] A 27, B 23, K 19, B 41. — ^{29}Al: [6] B 22; [8] B 22; [12] C 55, S 20, F 2, E 4, E 1, M 32, H 38, B 22; [23] P 28. — ^{27}Si: [6] K 13a; [8] B 9; M 2; [13] K 13a, K 13b; [16] K 32, M 13, C 48, B 9. — ^{28}Si: [17] H 39, G 6, P 9; [18] M 20. — ^{29}Si: [22] W 18. — ^{30}Si: [12] P 32, C 5, D 21, O 14, D 33, H 30, K 4, S 59, H 68a; [20] P 23a. — ^{31}Si: [6] C 15; [8] K 35; [9] N 13; [20] N 10, K 35, N 13; [21] A 27; [22] C 15; [23] A 27, B 23, C 15, W 17, R 7. — ^{29}P: [6] W 16a; [8] W 16a; [16] W 16a. — ^{30}P: [6] C 15; [8] M 2; B 9; [13] C 55, S 18, A 10, F 1, M 32, M 2, R 13, R 16, S 58; [14] C 36; [15] A 22; [16] L 53, B 5, B 9, W 16a; [19] S 1, H 57; [24] B 23, P 28, C 15; [25] B 46, B 51, B 53. — ^{31}P: [12] H 28, H 29. — ^{32}P: [6] C 3; compare $T = [14{,}07 \pm 0{,}01]$ d: M 43a; [8] L 55; L 21; M 43; [9] K 35; [12] F 2, K 12; [19] S 1; [20] N 10, K 35, N 13, L 55, C 3, L 21, P 22, W 22; [21] F 14, P 34, E 9; [22] A 27; [23] A 27, A 12, W 18, B 41, L 30, E 10, N 5a, G 14. — > ^{31}P: [6] C 36; [23] C 36. — ^{31}S: [6] E 2a; [8] W 16a; E 2a; [13] K 13a, K 13b, E 2a; [16] W 16a. — ^{32}S: [17] C 58, H 59. — ^{33}S: [19] S 34b; [20] P 18, S 39a. ^{34}S: [12] P 2, M 12, P 13. — ^{35}, ^{37}S: [6] L 27; [8] L 30; [20] V 10; [23] A 29, A 30, L 30, T 11, L 27, O 12a.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
17	**Cl**	16	33	—	[2.4 ± 0.2] *s*	β^+	4.13 ± 0.07	—	—	—
		17	34	—	[32 ± 1] *m*	β^+	2.5	—	—	—
		18	**35**	75.4	—	—	—	—	34.97884	0.19
		19	36	—	(> 1*a*) *)	β^+, K, β^-	0.7 (β^-)	—	35.97803	0.36
		20	**37**	24.6	—	—	—	—	36.97770	0.09
		21	38	—	37.5 *m*	β^-	1.1, 4.99 ± 0.06	1.65, 2.15	37.97999	0.32
18	**A**	17	35	—	[1.88 ± 0.04] *s*	β^+	4.38 ± 0.07; 4.41 ± 0.09	—	—	—
		18	**36**	0.31	—	—	—	—	35.97728	0.37
		20	**38**	0.06	—	—	—	—	37.97463	0.33
		22	**40**	99.63	—	—	—	—	39.97549	0.12
		23	41	—	[110 ± 1] *m*	β^-	1.5, (5)	1.37	40.97740	—
19	**K**	19	38	—	[7.65 ± 0.1] *m*	β^+	2.3	—	—	—
		20	**39**	93.44	—	—	—	—	38.976	1.6
		21	40	0.012	[14.2 ± 3.0] 10^8 *a*	β^-	0.725 ± 0.1	—	—	—
		22	**41**	6.55	—	—	—	—	—	—
		23	42	—	[12.4 ± 0.2] *h*	β^-	3.5	—	—	—
		24	43	—	[18 ± 1] *m*	β^-	—	—	—	—
		25	44	—	—	—	or —	—	—	—
20	**Ca**	(19)	(39)	—	[4.5 ± 0.5] *m*	β^+	—	—	—	—
		20	**40**	96.96	—	—	—	—	—	—
		21	41	—	[8.5 ± 0.8] *d*	*K*	—	1.1 ± 0.1	—	—
		22	**42**	0.64	—	—	—	—	—	—
		23	**43**	0.15	—	—	—	—	—	—
		24	**44**	2.07	—	—	—	—	—	—
		25	45	—	[180 ± 10] *d*	β^-	0.19±0.01 (95%) 0.91±0.03 (5%)	0.71 ± 0.03	44.97075	0.64
		26	**46**	0.003	—	—	—	—	—	—
		28	**48**	0.185	—	—	—	—	—	—
		29	49	—	[2.5 ± 0.1] *h*	β^-	2.3 ± 0.1	0.8 ± 0.1	—	—
		(isomer)		—	[30 ± 1] *m*	β^-	—	—	—	—
21	**Sc**	20	41	—	[0.87 ± 0.03] *s*	β^+	4.94 ± 0.07	—	—	—
		21	42	—	[13.4 ± 0.3] *d*	β^+	1.4	—	—	—
		22	43	—	[4.0 ± 0.1] *h*	β^+	0.4, 1.4	1.0	—	—
		23	44	—	[4.1 ± 0.1] *h*	β^+	1.45 ± 0.02; 1.6; 1.9	—	—	—
		isomer		—	[52 ± 2] *h*	γ	—	0.268 ± 0.005; 0.25	—	—
		24	**45**	100	—	—	—	—	44.96977	0.63
		25	46	—	[85 ± 1] *d*	β^-, *K*	0.26, 1.5	1.25	45.96909	0.70
		26	47	—	[63 ± 2] *h*	β^-	1.1	—	—	—
		27	48	—	[44 ± 1] *h*	β^-	0.5 [90%], 1.4 [10%]; 0.640 ± 0.007	0.9	—	—
		28	49	—	[57 ± 2] *m*	β^-	1.8 ± 0.1	none	—	—

^{33}Cl: [6] W 16a; [8] W 16a; [16] W 16a; [18] H 57. — ^{34}Cl: [6] R 16; [8] B 56; [14] F 25, R 16, B 56, S 34; [15] S 34; [18] S 1; [24] P 28; [25] B 53. — ^{35}Cl: [13] H 29, B 58. — ^{36}Cl: [6] G 16; [8] G 16; [20] G 16, P 22, S 32, S 34b; [21] G 16. *) Activity nonexistent according to O 12a; *T* would have to be > 1000 *a*. — ^{38}Cl: [6] H 70; [8] W 12b; [9] C 60; [19] K 35, K 7; [20] K 35, V 4, W 12b, C 60, P 22, S 32, S 34b; [21] A 27, A 11, R 3, E 7, E 8, K 7, S 32, O 12a; [22] H 70. — ^{35}A: [6] E 2a; [8] W 16a; E 2a; [14] K 13a, K 13b, E 2a; [16] W 16a. — ^{38}A: [13] P 13, M 2; [15] C 58. — ^{40}A: [13] P 13. — ^{41}A: [6] S 41; [8] K 35; [9] R 10; [20] K 35, S 41, R 10, D 6; [21] S 20; [23] H 70. — ^{38}K: [6] R 16; [8] R 16; [14] H 70, H 36, R 16, P 16; [19] H 70; [24] P 28. — ^{40}K: [6] B 55; [8] L 30; [14] P 15, P 16; [16] B 6; [20] P 22. — ^{42}K: [6] H 70; [8] K 35; [20] K 35, H 70; [21] A 27, W 2, H 70; [22] A 27, H 40, H 41, H 45, W 4, H 46; [23] H 42, H 70, B 41, H 46, W 5, W 10. — ^{43,44}K: [6] W 5; [23] W 5, W 10. — $^{(39)}$Ca: [6] W 10; [24] P 28, W 10. — ^{41}Ca: [6] W 10; [7] W 10; [9] W 10; [20] D 4, W 10; [24] W 10. — ^{42}Ca: [13] P 13. — ^{43}Ca: [14] P 15, P 16. — ^{45}Ca: [6] W 10; [8] W 10; [9] W 10;

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	(α, p)	(α, n)	(p, γ)	(p, n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	(α, d) or (α, pn)	$^{32}_{16}$S	—	$^{33}_{16}$S	—	—	—	—	—	—	—	^{33}Cl
—	—	$^{31}_{15}$P	$^{32}_{16}$S	—	—	$^{34}_{16}$S	—	—	—	—	—	$^{35}_{17}$Cl	$^{34}_{17}$Cl	^{34}Cl
—	$^{32}_{16}$S $^{(38)}_{18}$A	$^{38}_{19}$K	—	$^{35}_{18}$A	—	—	$^{33}_{16}$S	$^{36}_{17}$Cl	$^{(36}_{17}$Cl)	$^{32}_{15}$P	$^{35}_{16}$S	$^{34}_{17}$Cl or	$^{34}_{17}$Cl	^{35}Cl
—	—	—	—	—	—	—	—	$^{35}_{17}$Cl	$^{(35}_{17}$Cl) *)	—	—	—	—	^{34}Cl
—	$^{(40)}_{18}$A	$^{(40}_{19}$K)	$^{38}_{18}$A	—	—	—	—	$^{39}_{17}$Cl	$^{38}_{17}$Cl	—	$^{37}_{16}$S	—	—	^{37}Cl
—	—	—	—	—	—	—	$^{40}_{18}$A	$^{37}_{17}$Cl	$^{37}_{17}$Cl	$^{41}_{19}$K	—	—	—	^{38}Cl
—	—	$^{32}_{16}$S	—	$^{35}_{17}$Cl	—	—	—	—	—	—	—	—	—	^{35}A
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{36}A
—	$^{(36)}_{17}$Cl	—	$^{37}_{17}$Cl	—	—	—	—	—	—	—	—	—	—	^{38}A
—	$^{(37)}_{17}$Cl	$^{43}_{20}$Ca	—	$^{40}_{19}$K	—	—	$^{38}_{17}$Cl	$^{41}_{18}$A	$^{41}_{18}$A	—	—	—	—	^{40}A
—	—	—	—	—	—	—	—	$^{42}_{18}$A	$^{42}_{18}$A	—	$^{41}_{19}$K	—	—	^{41}A
—	—	$^{35}_{17}$Cl	—	—	—	—	$^{40}_{20}$Ca	—	—	—	—	$^{39}_{19}$K	—	^{38}K
—	$^{42}_{20}$Ca	$^{42}_{21}$Sc	—	—	—	—	—	$^{40}_{19}$K	—	—	—	$^{38}_{19}$K	—	^{39}K
—	—	$^{(37}_{17}$Cl)	—	$^{40}_{18}$A	—	—	—	$^{39}_{19}$K	—	—	—	—	—	^{40}K
—	—	$^{44}_{21}$Sc	—	—	—	—	—	$^{43}_{19}$K	$^{42}_{19}$K	$^{38}_{17}$Cl	$^{41}_{18}$A	—	—	^{41}K
—	—	—	—	—	—	—	—	$^{41}_{19}$K	$^{41}_{19}$K	$^{45}_{21}$Sc	$^{42}_{20}$Ca	—	—	^{42}K
—	—	—	—	—	—	—	—	—	—	or	$^{43}_{20}$Ca	—	—	^{43}K
—	—	—	—	—	—	—	—	—	—		$^{44}_{20}$Ca	—	—	^{44}K
—	—	—	—	—	—	—	—	—	—	—	—	($^{40}_{20}$Ca)	—	$^{(39)}$Ca
—	$^{43}_{21}$Sc	—	—	—	—	$^{41}_{21}$Sc	$^{38}_{19}$K	$^{41}_{20}$Ca	—	—	—	($^{38}_{20}$Ca)	—	^{40}Ca
—	—	—	—	—	—	—	—	$^{42}_{20}$Ca	—	—	—	$^{42}_{20}$Ca	—	^{41}Ca
—	$^{39}_{19}$K	—	—	—	—	$^{43}_{21}$Sc or	—	—	—	—	$^{42}_{19}$K	$^{41}_{20}$Ca	—	^{42}Ca
—	$^{46}_{21}$Sc	$^{40}_{18}$A	—	—	—	$^{44}_{21}$Sc	—	—	—	—	$^{43}_{19}$K or	—	—	^{43}Ca
—	$^{47}_{21}$Sc	—	—	$^{44}_{21}$Sc	$^{44}_{21}$Sc	—	—	$^{45}_{20}$Ca	$^{45}_{20}$Ca	—	$^{44}_{19}$K	—	—	^{44}Ca
—	—	—	—	—	—	—	—	$^{46}_{20}$Ca	$^{46}_{20}$Ca	—	$^{45}_{21}$Sc	—	—	^{45}Ca
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{46}Ca
—	—	—	($^{49}_{21}$Sc)	—	$^{48}_{21}$Sc	$^{49}_{21}$Sc	—	$^{49}_{20}$Ca	$^{49}_{20}$Ca	—	—	—	—	^{48}Ca
$^{49}_{21}$Sc	—	—	—	—	—	—	—	$^{48}_{20}$Ca	$^{48}_{20}$Ca	—	—	—	—	^{49}Ca
—	—	—	—	—	—	—	—	$^{48}_{20}$Ca	$^{48}_{20}$Ca	—	—	—	—	^{49}Ca*
—	—	—	—	—	—	$^{42}_{20}$Ca	—	—	—	—	—	—	—	^{41}Sc
—	—	$^{39}_{19}$K	—	—	—	—	—	—	—	—	—	—	—	^{42}Sc
—	$^{42}_{20}$Ca	—	—	—	—	$^{42}_{20}$Ca— or	—	—	—	—	—	—	—	^{43}Sc
$^{44}_{21}$Sc*	—	$^{41}_{19}$K	—	$^{44}_{20}$Ca	$^{44}_{20}$Ca	$^{42}_{20}$Ca—	—	—	—	—	—	$^{45}_{21}$Sc	$^{45}_{21}$Sc	^{44}Sc
$^{44}_{21}$Sc	—	$^{41}_{19}$K	—	$^{44}_{20}$Ca	$^{44}_{20}$Ca	$^{42}_{20}$Ca	($^{46}_{22}$Ti)	—	—	—	—	$^{44}_{21}$Sc	—	^{44}Sc*
—	$^{48}_{22}$Ti	$^{46}_{23}$V	—	—	—	—	—	$^{46}_{21}$Sc	$^{46}_{21}$Sc	$^{42}_{19}$K	$^{45}_{20}$Ca	$^{44}_{21}$Sc	$^{44}_{21}$Sc	^{45}Sc
—	$^{42}_{20}$Ca	—	—	—	—	—	($^{48}_{22}$Ti)	$^{45}_{21}$Sc	$^{45}_{21}$Sc	—	($^{46}_{22}$Ti)	—	—	^{46}Sc
—	$^{44}_{20}$Ca	—	—	—	—	—	—	—	—	—	($^{47}_{22}$Ti)	—	—	^{47}Sc
—	—	—	—	—	$^{46}_{20}$Ca	—	—	—	—	$^{51}_{23}$V	$^{48}_{22}$Ti	—	—	^{48}Sc
$^{48}_{20}$Ca	—	—	($^{48}_{20}$Ca)	—	—	$^{48}_{20}$Ca	—	—	—	—	$^{47}_{22}$Ti	—	—	^{49}Sc

[20] W 10; [21] W 10; [23] W 10. — ^{49}Ca: [6] W 10; [8] W 10; [9] W 10; [20] W 2, W 10; [21] H 45, W 2, W 10. — ^{49}Ca*: [3, 4] W 10; [6] W 10; [20] W 2, W 10; [21] W 2, W 10. — ^{41}Sc: [6] E 2a; [8] E 2a; [18] K 13b, E 2a. — ^{42}Sc: [6] W 8; [8] W 8; [14] W 8. — ^{43}Sc: [6] W 3; [8] W 3, W 8; [9] W 8; [13] F 26, P 14, W 2, W 3, S 12, W 8; [18] W 2. — ^{44}Sc: [6] W 2; [8] S 40a; W 3; M 2; [12] W 8; [14] Z 2, W 2, W 3, M 2, W 8; [16] D 28; [17] S 40a; [18] W 2; [24] P 28, W 4, C 32; [25] G 7, B 64, B 53. — ^{44}Sc*: [3, 4] B 64, C 32, W 8; [6] W 2; [7] W 8; [9] S 40a; W 8; [14] Z 2, W 2, W 8; [16] D 28; [17] S 40a; [18] W 2; [19] W 6; [24] P 28, W 4, C 32. — ^{44}Sc: [6] W 4, W 7; [8] W 8; [9] W 8; [13] W 8; [19] W 6; [20] W 4, C 32, D 5, W 7; [21] H 45, W 4, H 46, C 32, W 8; [23] W 6. — ^{47}Sc: [6] W 8; [8] W 8; [13] W 8; [23] W 8. — ^{48}Sc: [6] W 8; [8] W 8; S 40a; [9] W 8; [17] S 40a; [22] P 28, W 6, W 8; [23] W 6, W 8. — ^{49}Sc: [6] W 8; [8] W 8; [9] W 8; [12] W 8; [15] D 28; [18] W 2, W 6, W 8; [23] P 28, W 8.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
22	**Ti**	**24**	**46**	7.95	—	—	—	—	—	—
		25	**47**	7.75	—	—	—	—	—	—
		26	**48**	73.45	—	—	—	—	47.96570	0.38
		27	**49**	5.51	—	—	—	—	48.964	2.0
		28	**50**	5.34	—	—	—	—	49.963	2.0
		29	51	—	[72 ± 2] *d*	β^-	0.36	1.0	—	—
		isomer		—	[2.9 ± 0.1] *m*	β^-	—	—	—	—
23	**V**	(24)	(47)	—	—	—	—	—	—	—
		25	48	—	[16.0 ± 0.2] *d*	β^+, *K*	or 1.0_5	1.05	—	—
		26	49	—	[600 ± 50] *d*	*K*	none β^+ or e^-	none	—	—
		isomer		—	[33 ± 1] *m*	β^+	1.9	—	—	—
		27	50	—	[3.7 ± 0.2] *h*	β^+	—	—	—	—
		28	**51**	100	—	—	—	—	50.96035	0.63
		29	52	—	[3.9 ± 0.1] *m*	β^-	1.98	—	51.95857	0.70
24	**Cr**	**26**	**50**	4.49	—	—	—	—	—	—
		27	51	—	[26.5 ± 1.0] *d*	*K*, (β^+)	< 0.1	(0.5), 1	—	—
		28	**52**	83.78	—	—	—	—	51.959	0.9
		29	**53**	9.43	—	—	—	—	—	—
		30	**54**	2.30	—	—	—	—	—	—
		31	55	—	1.7 *h*	β^-	—	—	—	—
25	**Mn**	26	51	—	[46 ± 2] *m*	β^+	2.0	—	—	—
		27	52	—	[6.5 ± 1.0] *d*	*K*, β^+	*K*[95%], β^+[5%]:0.77	1.0	—	—
		isomer		—	[21 ± 2] *m*	β^+	2.2	1.2	—	—
		29	54	—	[310 ± 20] *d*	*K*	—	0.85	—	—
		30	**55**	100	—	—	1.035 ± 0.15, 2.88 ± 0.01; (*o.6*), 1.15, 2.84 ± 0.05; *1.2, 2.9*; 2.7 ± 0.2	—	—	—
		31	56	—	[2.59 ± 0.02] *h*	β^-		1.65; 1.2; 0.91, 2.03; 0.6—0.7, 1.7	—	—
26	**Fe**	27	53	—	[8.9 ± 0.2] *m*	β^+	—	—	—	—
		28	**54**	5.84	—	—	—	—	53.961	2.4
		29	55	—	~4 *a*	(K, β^+)	—	—	—	—
		30	**56**	91.68	—	—	—	—	55.9571	1.8
		31	**57**	2.17	—	—	—	—	—	—
		32	**58**	0.31	—	—	—	—	—	—
		33	59	—	[57 ± 3] *d*	β^-	0.4, 0.9	1	—	—
27	**Co**	29	56	—	270 *d*	*K*, (β^+)	(β^+) : 0.4; 1.36 ± 0.10	0.1, (0.9); 0.119, 0.132	—	—
		30	57	—	18.2 *h*	β^+	1.5 or	0.1, 0.22, 0.8, 1.2	or	—
		31	58	—	70 *d*	β^+	< 0.5;	0.6;	—	—
		32	**59**	100	—	—	—	—	—	—
		33	60	—	7 *a*	β^-	0.16, 1.45 ± 0.10	1.3	—	—
		(isomer)		—	11 *m*	β^-	—	—	—	—

^{48}Ti: [13] P 17. — ^{51}Ti: [6] W 7; [8] W 7; [9] W 7; [20] W 7; [21] W 11. — ^{51}Ti*: [3, 4] W 7; [6] W 6; [20] W 6; [21] A 27, W 6. — ^{48}V: [6] W 6; [7] A 19, A 21, W 7; [8] W 6; [9] R 11; [14] W 4, P 16; [16] D 32; [18] W 6, A 19, R 11, W 7; [19] W 6. — $^{(47),49}$V: [6] W 7; [7] W 7; [8] W 7; [9] W 7; [18] W 7. — ^{49}V*: [3, 4] T 11a; [6] W 6; [8] W 6; [13] W 6; [16] D 32; [18] W 6. — ^{50}V: [6] W 6; [13] W 6; [18] W 6; [23] A 26; [24] W 6. — ^{51}V: [13] D 3. — ^{52}V: W 6; [8] G 1; [20] W 6, D 5; [21] A 27, P 28, W 6, G 1; [22] A 27, B 41, P 28, W 6; [23] A 27, B 41, P 28, W 6. — ^{51}Cr: [6] W 9; [7] W 9; [8] W 9; [9] W 9; [14] W 9; [20] W 9. A 26; [21] W 9, A 26; [24] A 26. — ^{53}Cr: [6] A 26; [20] A 26; [21] P 28, A 26, D 20. — ^{51}Mn: [6] L 43; [8] L 43; [15] D 28, D 18; [18] L 35, L 43. — ^{52}Mn: [6] L 43; [7] H 32; [8] H 32; [9] H 32; [16] H 32; [19] L 35, L 43. — ^{52}Mn*: [3, 4] L 43; [6] L 43; [8] H 32; [9] H 32; [16] H 32; [19] D 2, L 35, L 43, F 5. — ^{54}Mn: [6] L 43; [7] L 43; [9] L 43; [14] L 43; [16] D 32; [18] L 43; [19] L 35, L 43; [25] *) compare ($^{55}_{25}$Mn (γ, n) $^{54}_{25}$Mn) $T \simeq 20$ *m*: C 4. — ^{56}Mn: [6] L 43; [8] T 9a; D 37; B 2a; G 2, B 59, B 1, N 21, L 3; L 43; [9] M 38; L 43; C 60; D 37, B 2a; [13] H 37, R 16, L 43; [19] L 35, L 43; [20] D 2, L 43, D 5, C 60,

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	(α, p)	(α, n)	(p, γ)	(p, n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	$^{49}_{23}$V	—	—	—	—	┌$^{(47)}_{23}$V	$^{(44}_{21}$Sc)	—	—	—	$^{(46}_{21}$Sc)	—	—	^{46}Ti
—	$^{50}_{23}$V	—	—	—	—	or $^{48}_{23}$V	—	—	—	—	$^{(47}_{21}$Sc)	—	—	^{47}Ti
—	$^{45}_{21}$Sc $^{51}_{23}$V	$^{51}_{24}$Cr	—	$^{48}_{23}$V	—	└ $^{49}_{23}$V	$^{(46}_{21}$Sc)	—	—	—	$^{48}_{21}$Sc	—	—	^{48}Ti
—	—	—	—	$^{49}_{23}$V	—	$^{50}_{23}$V	—	—	—	—	$^{49}_{21}$Sc	—	—	^{49}Ti
—	—	—	—	—	—	—	—	$^{51}_{22}$Ti	$^{51}_{22}$Ti	—	—	—	—	^{50}Ti
—	—	—	—	—	—	—	—	$^{50}_{22}$Ti	$^{50}_{22}$Ti	—	—	—	—	^{51}Ti
—	—	—	—	—	—	—	—	$^{50}_{22}$Ti	$^{50}_{22}$Ti	—	—	—	—	^{51}Ti*
—	—	—	—	—	┌	$^{46}_{22}$Ti	—	—	—	—	—	—	—	^{47}V
—	—	$^{45}_{21}$Sc	—	$^{48}_{22}$Ti	or	$^{47}_{22}$Ti	$^{50}_{24}$Cr	—	—	—	—	—	—	^{46}V
—	—	—	—	—	└	$^{48}_{22}$Ti	—	—	—	—	—	—	—	^{49}V
—	$^{46}_{22}$Ti	—	—	$^{49}_{22}$Ti	—	$^{48}_{22}$Ti	—	—	—	—	—	—	—	^{49}V*
—	$^{47}_{22}$Ti	—	—	—	—	$^{49}_{22}$Ti	—	—	—	—	$^{(50}_{24}$Cr)	$^{51}_{23}$V	—	^{50}V
—	$^{48}_{22}$Ti	$^{54}_{25}$Mn	—	—	—	—	—	$^{52}_{23}$V	$^{52}_{23}$V	$^{48}_{21}$Sc	—	$^{50}_{23}$V	—	^{51}V
—	—	—	—	—	—	—	—	$^{51}_{23}$V	$^{51}_{23}$V	$^{55}_{25}$Mn	$^{52}_{24}$Cr	—	—	^{52}V
—	—	$^{52}_{26}$Fe	$^{51}_{25}$Mn	—	—	$^{51}_{25}$Mn	$^{48}_{23}$V	$^{51}_{24}$Cr	$^{51}_{24}$Cr	—	$^{(50}_{23}$V)	—	—	^{50}Cr
—	—	$^{49}_{22}$Ti	—	—	—	—	—	$^{50}_{24}$Cr	$^{50}_{24}$Cr	—	—	$^{(52}_{24}$Cr)	—	^{51}Cr
—	—	—	—	$^{52}_{25}$Mn	—	—	—	—	—	—	$^{52}_{23}$V	$^{(51}_{24}$Cr)	—	^{52}Cr
—	$^{56}_{25}$Mn	—	—	—	—	$^{54}_{25}$Mn	—	—	—	—	—	—	—	^{53}Cr
—	—	—	—	$^{54}_{25}$Mn	—	—	—	$^{55}_{24}$Cr	$^{55}_{24}$Cr	—	—	—	—	^{54}Cr
—	—	—	—	—	—	—	—	$^{54}_{24}$Cr	$^{54}_{24}$Cr	—	—	—	—	^{55}Cr
—	—	—	$^{50}_{24}$Cr	—	—	$^{50}_{24}$Cr	—	—	—	—	—	—	—	^{51}Mn
—	—	—	—	$^{52}_{24}$Cr	—	—	$^{54}_{26}$Fe	—	—	—	—	—	—	^{52}Mn
—	—	—	—	$^{52}_{24}$Cr	—	—	$^{54}_{26}$Fe	—	—	—	—	—	—	^{52}Mn*
—	—	$^{51}_{23}$V	—	$^{54}_{24}$Cr	—	$^{53}_{24}$Cr	$^{56}_{26}$Fe	—	—	—	—	—	*)	^{54}Mn
—	—	$^{58}_{27}$Co	—	$^{55}_{26}$Fe	—	—	—	$^{56}_{25}$Mn	$^{56}_{25}$Mn	$^{52}_{23}$V	—	—	—	^{55}Mn
—	$^{53}_{24}$Cr	—	—	—	—	—	$^{58}_{26}$Fe	$^{55}_{25}$Mn	$^{55}_{25}$Mn	$^{59}_{27}$Co	$^{56}_{26}$Fe	—	—	^{56}Mn
—	—	$^{50}_{24}$Cr	—	—	—	—	—	—	—	—	—	$^{54}_{26}$Fe	—	^{53}Fe
—	—	$^{57}_{28}$Ni	—	—	—	—	$^{52}_{25}$Mn	$^{55}_{26}$Fe	—	—	—	$^{53}_{26}$Fe	—	^{54}Fe
—	—	—	—	$^{55}_{25}$Mn	—	—	—	$^{54}_{26}$Fe	—	—	—	—	*)	^{55}Fe
—	—	$^{(59)}_{28}$Ni	$^{57}_{27}$Co	$^{56}_{27}$Co	$^{56}_{27}$Co	$^{57}_{27}$Co	$^{54}_{25}$Mn	—	—	—	$^{56}_{25}$Mn	—	—	^{56}Fe
—	—	—	$^{58}_{27}$Co	—	—	$^{58}_{27}$Co	—	—	—	—	—	—	—	^{57}Fe
—	—	—	└ or	$^{58}_{27}$Co	—	—	$^{56}_{25}$Mn	$^{56}_{26}$Fe	—	—	—	—	—	^{56}Fe
—	—	—	—	—	—	—	—	$^{58}_{26}$Fe	—	—	$^{59}_{27}$Co	—	—	^{59}Fe
—	—	—	—	$^{56}_{26}$Fe	$^{56}_{26}$Fe	—	$^{59}_{28}$Ni	—	—	—	—	—	—	^{56}Co
—	—	—	$^{56}_{26}$Fe	—	—	$^{56}_{26}$Fe	—	—	—	—	—	—	—	^{57}Co
—	—	$^{55}_{25}$Mn	$^{57}_{26}$Fe	$^{58}_{26}$Fe	—	$^{57}_{26}$Fe	$^{60}_{28}$Ni	—	—	—	$^{58}_{28}$Ni	—	—	^{58}Co
—	—	$^{62}_{29}$Cu	└ or	└	—	—	—	$^{60}_{27}$Co	$^{60}_{27}$Co	$^{56}_{25}$Mn	$^{59}_{26}$Fe	—	—	^{59}Co
—	—	—	—	—	—	—	—	$^{59}_{27}$Co	$^{59}_{27}$Co	—	$^{60}_{28}$Ni	—	—	^{60}Co
—	—	—	—	—	—	—	—	—	$^{59}_{27}$Co	—	$^{(60)}_{28}$Ni	—	—	$^{(60)}$Co*

T 9a; [21] A 27, A 12, G 2, B 59, M 38, P 28, B 1, L 43, N 21, L 3, D 37, B 2a; [22] A 27, P 28, B 41, L 43; [23] A 27, P 28, L 43. — ^{48}Fe: [6] L 40; [14] H 37, R 16, L 40; [24] L 40. — ^{53}Fe: [6] L 48, V 6; [7] L 48; [16] V 6; [20] L 48; [25] *) compare ($^{56}_{26}$Fe (γ, n) $^{55}_{26}$Fe) $T \simeq$ 60—90 *m*: C 4. — ^{59}Fe: [6] L 40; [8] L 40; [9] L 40; [20] L 35, L 40; [23] A 31, L 35, L 40. — ^{56}Co: [6] L 38, L 49; [7] L 49; [8] L 49; J 3a; [9] J 3a; P 9a; [16] L 38; [17] P 8, L 38, B 14, J 3a, P 9a; [19] L 37, L 49. — ^{57}Co: [3, 4] Classified arbitrarily by L 49 as ^{58}Co, assuming the existence of a stable ^{57}Co despite unsatisfactory mass spectrographic confirmation; *cf.* H 17; [6] D 2; [8] L 21; [9] C 64; [15] L 38; [18] D 2, L 35, C 64, L 21. — ^{58}Co: [6] L 38, L 49; [8] L 49; J 3a; [9] L 49; J 3a; P 9a; [14] P 16, L 38; [15] or [16] L 38; [18] P 8, L 38, B 14, J 3a, P 9a; [19] L 37, L 49; [23] V 9, L 49. — ^{60}Co: [6] S 26, L 49; [8] R 18; [9] L 38; [20] L 38, D 7; [21] S 14, L 35, R 18, L 38; [23] V 9. — $^{(60)}$Co*: [3, 4] R 18; [6] H 50; [21] R 25, H 49, L 35; [23] R 25, H 49, H 50.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
28	**Ni**	29	57	—	[36 ± 2] *h*	β^+	0.67 ± 0.1	—	—	—
		30	**58**	67.4	—	—	—	—	57.95971	0.41
		(31)	(59)	—	?	—	—	—	—	—
		32	**60**	26.7	—	—	—	—	59.94981	0.33
		33	**61**	1.2	—	—	—	—	60.9540	1.5
		34	**62**	3.8	—	—	—	—	61.94959	0.39
		35	63	—	[2.6 ± 0.03] *h*	β^-	*0.67, 1.65*	1.1	—	—
		36	**64**	0.88	—	—	—	—	63.94744	0.56
29	**Cu**	29	58	—	[81 ± 2] *s*	β^+	—	—	—	—
		31	60	—	[7.9 ± 0.5] *m*	β^+	or —	—	—	—
		32	61	—	[3.4 ± 0.1] *h*	β^+, *K*	0.94	none	—	—
		33	62	—	[9.92 ± 0.05] *m*	β^+	2.6; *3.42*	—	—	—
		34	**63**	68	—	—	β^+: 0.659 ± 0.003; 0.649 ± 0.004	—	62.957	1.3
		35	64	—	[12.8 ± 0.3] *h*	β^-, β^+, *K*	β^-: 0.578 ± 0.003; 0.574 ± 0.004	none	—	—
		36	**65**	32	—	—		—	64.955	1.3
		37	66	—	[5 ± 1] *m*	β^-	2.58; *2.91*	—	—	—
30	**Zn**	33	63	—	[38.3 ± 0.5] *m*	β^+	2.320 ± 0.005; 2.3 ± 0.15; 1.8; *1.92*		—	—
		34	**64**	50.9	—	—	—	—	63.957	2.7
		35	65	—	[250 ± 5] *d*	*K*, β^+	0.47; *0.19 0.37*	0.45, 0.65, 1.0 (*K*)	—	—
		36	**66**	27.3	—	—	—	—	65.953	2.8
		37	**67**	3.9	—	—	—	—	—	—
		38	**68**	17.4	—	—	—	—	67.955	3.5
		39	69	—	[57 ± 2] *m*	β^-	1.0; *0.99*	none	—	—
		isomer		—	[13.8 ± 0.4] *h*	γ	—	0.47	—	—
		40	**70**	0.5	—	—	—	—	69.954	3.7
31	**Ga**	33	64	—	[48 ± 2] *m*	β^+	—	—	—	—
		34	65	—	15 *m*	*K*	—	0.0538, 0.1170	—	—
		35	66	—	[9.2 ± 0.2] *h*	β^+	3.1 (3.9)	—	—	—
		36	67	—	[79 ± 2] *h*	*K*	—	0.0925; 0.1, 0.25	—	—
		37	68	—	[1.10 ± 0.05] *h*	β^+	1.8 (1.9); 1.85; *1.37*	—	—	—
		38	**69**	61.2	—	—	—	—	68.956	3.5
		39	70	—	[19.8 ± 0.4] *m*	β^-, *K*	2.6; 5.0; *1.68*	—	—	—
		40	**71**	38.8	—	—	—	—	70.954	3.6
		41	72	—	[14.1 ± 0.2] *h*	β^-	2.6; *1.71*	1.0	—	—
	*)	(43)	(74)	—	~ 9 *d*	β^-	0.8	—	—	—
32	**Ge**	(37)	(69)	—	195 *d*	—	—	—	—	—
		38	**70**	21.2	—	—	or —	—	—	—
		39	71	—	[37 ± 1.5] *h*	β^+	1.2; *1.15*; 1.0	—	—	—
	**)	(isomer)		—	11 *d*	(*K*)	—	(0.6)	—	—
		40	**72**	27.3	—	—	—	—	—	—
		41	**73**	7.9	—	—	—	—	—	—

^{57}Ni: [6] L 37; [8] L 37; [14] L 37; [24] L 37. — $^{(59)}$Ni: [14] P 16. — ^{63}Ni: [6] L 37; [8] S 8; [9] L 37; [20] T 6, L 37; [21] R 25, N 3, O 1, H 50; [22] M 1, H 50; [23] O 1, H 50, S 6, S 8; [24] H 50. — ^{58}Cu: [6] D 18; [16] R 17, D 18. — ^{60}Cu: [6] D 18; [16] R 17, D 18. — ^{61}Cu: [6] R 17; [7] A 21; [8] R 16; [9] G 8; [13] R 14, R 15, R 16; [15] D 18; [16] R 17, S 55, D 18, W 14; [18] T 8, A 21, G 8. — ^{62}Cu: [6] C 51; [8] C 51; S 35; [14] R 14, H 37, R 16; [15] S 55; [16] S 55; [22] K 27, G 13a; [24] C 13, H 48, P 26, H 49, H 50, P 28, R 27, S 2, S 35, S 6, C 51; [25] B 46, C 13, B 51, B 53, S 6. — ^{64}Cu: [6] R 17; [7] V 5, A 21, A 18; [8] β^+: T 13; T 9a; β^-: T 13; T 9a; [9] T 13; [16] R 17, S 55, D 18; [19] L 33; [20] V 5, S 35, A 21, S 6, R 9, T 13, D 5, N 14, L 54a, N 14a; [21] A 27, B 24, H 50, S 2, S 6; [23] A 27, B 24, O 1, H 50, S 6, W 14; [24] P 26, H 50, P 28, S 2, S 6. — ^{66}Cu: [6] S 6; [8] G 1; S 35; [20] L 33, S 6, D 5, N 14a; [21] A 27, H 48, S 2, S 35, S 6, G 1; [22] C 13; [23] B 24 A 27, H 48, H 50, S 6. — ^{63}Zn: [6] S 55; [8] T 9a; S 55; D 18; S 8; [14] R 14, R 15, R 16; [16] R 17, S 55, D 18, W 14; [17] L 54a, T 9a; [24] H 48, P 28, H 50, R 27, S 2, T 9, S 6, S 8; [25] B 48, C 13, B 51, B 52, B 53. — ^{65}Zn: [6] L 46; [7] A 21, L 46, W 12c; [8] W 12c; S 8; [9] W 12c; [12] L 49; [16] B 11, S 55, D 18; [17] L 33, P 8, S 6, L 46, S 8; [20] L 42, L 46, K 6, W 12c; [21] S 6. — ^{69}Zn: [6] L 46; [8] L 46; S 8; [9] L 46; [12] K 6; [19] L 46; [20] L 33, T 9, L 46, V 3, K 6; [21] M 17, H 48,

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	(α, p)	(α, n)	(p, γ)	(p, n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	$^{54}_{26}$Fe	—	—	—	—	—	—	—	—	—	($^{58}_{28}$Ni)	—	^{57}Ni
—	$^{61}_{29}$Cu	—	—	$^{58}_{29}$Cu	—	—	$^{56}_{27}$Co	—	—	—	$^{58}_{27}$Co	($^{57}_{28}$Ni)	—	^{58}Ni
—	—	($^{59}_{26}$)Fe	—	—	—	—	—	—	—	—	—	—	—	(^{59})Ni
—	—	$^{63}_{30}$Zn	$^{61}_{29}$Cu	$^{60}_{29}$Cu	—	$^{61}_{29}$Cu	$^{58}_{27}$Co	—	—	—	$^{60}_{27}$Co	—	—	^{60}Ni
—	—	—	$^{62}_{29}$Cu	$^{61}_{29}$Cu	—	—	—	—	—	—	—	—	—	^{61}Ni
—	—	—	—	$^{62}_{29}$Cu	—	—	—	$^{63}_{28}$Ni	$^{63}_{28}$Ni	—	—	—	—	^{62}Ni
—	—	—	—	—	—	—	—	$^{62}_{28}$Ni	$^{63}_{28}$Ni	$^{66}_{30}$Zn	$^{63}_{29}$Cu	$^{64}_{28}$Ni	—	^{63}Ni
—	—	—	—	$^{64}_{29}$Cu	—	—	—	—	—	—	—	$^{63}_{28}$Ni	—	^{64}Ni
—	—	—	—	$^{56}_{28}$Ni	—	—	—	—	—	(d, $^{3}_{1}$H)	—	—	—	^{58}Cu
—	—	—	—	$^{60}_{28}$Ni	—	—	—	—	—	—	—	—	—	^{60}Cu
—	$^{59}_{28}$Ni	—	$^{60}_{28}$Ni	$^{61}_{28}$Ni	—	$^{60}_{28}$Ni	—	—	—	—	—	—	—	^{61}Cu
—	—	$^{59}_{27}$Co	$^{62}_{28}$Ni	$^{62}_{28}$Ni	—	—	—	—	—	$^{62}_{29}$Cu	—	$^{62}_{29}$Cu	$^{62}_{29}$Cu	^{62}Cu
—	—	$^{66}_{31}$Ga	—	$^{63}_{30}$Zn	$^{63}_{30}$Zn	—	—	$^{64}_{29}$Cu	$^{64}_{29}$Cu	$^{62}_{29}$Cu	$^{63}_{28}$Ni	$^{62}_{29}$Cu	$^{62}_{29}$Cu	^{63}Cu
—	—	—	—	$^{64}_{28}$Ni	—	—	($^{65}_{30}$Zn)	$^{63}_{29}$Cu	$^{63}_{29}$Cu	—	$^{66}_{30}$Zn	$^{65}_{29}$Cu	—	^{64}Cu
—	—	$^{68}_{31}$Ga	—	$^{65}_{30}$Zn	$^{65}_{30}$Zn	—	—	$^{66}_{29}$Cu	$^{66}_{29}$Cu	—	—	$^{64}_{29}$Cu	—	^{65}Cu
—	—	—	—	—	—	—	—	$^{65}_{29}$Cu	$^{65}_{29}$Cu	$^{69}_{31}$Ga	$^{66}_{30}$Zn	—	—	^{66}Cu
—	—	$^{69}_{28}$Ni	—	$^{62}_{29}$Cu	$^{63}_{29}$Cu	—	—	—	—	—	—	$^{64}_{30}$Zn	$^{64}_{30}$Zn	^{63}Zn
—	$^{67}_{31}$Ga	—	$^{65}_{31}$Ga	$^{64}_{31}$Ga	—	$^{65}_{31}$Ga	—	$^{65}_{30}$Zn	$^{65}_{30}$Zn	—	$^{64}_{29}$Cu	$^{63}_{30}$Zn	$^{63}_{30}$Zn	^{64}Zn
$^{65}_{31}$Ga	—	—	—	$^{65}_{29}$Cu	$^{65}_{29}$Cu	—	—	$^{64}_{30}$Zn	$^{64}_{30}$Zn	—	—	—	—	^{65}Zn
—	—	($^{69}_{32}$)Ge	—	$^{66}_{31}$Ga	—	$^{67}_{31}$Ga	($^{64}_{29}$Cu)	—	—	$^{63}_{28}$Ni	$^{66}_{29}$Cu	—	—	^{66}Zn
—	$^{70}_{31}$Ga	—	($^{68}_{31}$Ga)	$^{67}_{31}$Ga	—	$^{68}_{31}$Ga	—	—	—	—	—	—	—	^{67}Zn
—	—	$^{71}_{32}$Ge	—	$^{66}_{31}$Ga	—	—	—	$^{68}_{30}$Zn	$^{68}_{30}$Zn	—	—	—	—	^{68}Zn
$^{69}_{30}$Zn*	—	—	—	—	—	—	$^{71}_{31}$Ga	$^{68}_{30}$Zn	$^{68}_{30}$Zn	—	$^{69}_{31}$Ga	—	—	^{69}Zn
$^{69}_{30}$Zn	—	—	—	—	—	—	$^{71}_{31}$Ga	$^{68}_{30}$Zn	$^{68}_{30}$Zn	—	$^{69}_{31}$Ga	—	—	^{69}Zn*
—	—	—	—	$^{70}_{31}$Ga	—	—	—	—	—	—	—	—	—	^{70}Zn
—	—	—	—	$^{64}_{30}$Zn	—	—	—	—	—	—	—	—	—	^{64}Ga
—	—	—	$^{66}_{30}$Zn	—	—	$^{66}_{30}$Zn	—	—	—	—	—	—	—	^{65}Ga
—	—	$^{63}_{29}$Cu	—	$^{66}_{30}$Zn	—	—	—	—	—	—	—	—	—	^{66}Ga
—	$^{64}_{30}$Zn	—	—	$^{67}_{30}$Zn	—	$^{66}_{30}$Zn	—	—	—	—	—	—	—	^{67}Ga
—	—	$^{65}_{29}$Cu	($^{67}_{30}$Zn	$^{68}_{30}$Zn	—	$^{67}_{30}$Zn	$^{70}_{32}$Ge	—	—	—	—	$^{69}_{31}$Ga	$^{69}_{31}$Ga	^{68}Ga
—	—	—	—	—	—	—	—	$^{70}_{31}$Ga	$^{70}_{31}$Ga	$^{66}_{29}$Cu	$^{69}_{30}$Zn	$^{68}_{31}$Ga	$^{68}_{31}$Ga	^{69}Ga
—	$^{67}_{30}$Zn	—	—	$^{70}_{30}$Zn	—	—	$^{72}_{32}$Ge	$^{69}_{31}$Ga	$^{69}_{31}$Ga	—	$^{70}_{32}$Ge	$^{71}_{31}$Ga	$^{71}_{31}$Ga	^{70}Ga
—	—	—	—	—	$^{71}_{32}$Ge	—	$^{69}_{30}$Zn	$^{72}_{31}$Ga	$^{72}_{31}$Ga	—	—	$^{70}_{31}$Ga	$^{70}_{31}$Ga	^{71}Ga
—	—	—	—	—	—	—	$^{74}_{32}$Ge	$^{71}_{31}$Ga	$^{71}_{31}$Ga	—	$^{72}_{32}$Ge	—	—	^{72}Ga
—	—	—	—	—	—	—	($^{76}_{32}$)Ge	—	—	—	($^{74}_{32}$Ge)	—	—	(^{74})Ga
—	—	($^{66}_{30}$)Zn	—	—	—	—	—	—	—	—	—	—	—	(^{69})Ge
—	—	—	—	—	—	—	$^{68}_{31}$Ga	$^{71}_{32}$Ge	$^{71}_{32}$Ge	—	$^{70}_{31}$Ga	—	—	^{70}Ge
—	—	$^{68}_{30}$Zn	—	—	$^{71}_{31}$Ga	—	or	$^{70}_{32}$Ge	$^{70}_{32}$Ge	$^{74}_{34}$Se	—	$^{72}_{32}$Ge	—	^{71}Ge
—	—	—	—	—	($^{72}_{31}$)Ga	—	—	($^{70}_{32}$)Ge	—	—	—	—	—	(^{71})Ge*
—	—	—	—	($^{72}_{33}$)As	—	$^{72}_{33}$As	$^{70}_{31}$Ga	—	—	—	$^{72}_{31}$Ga	$^{71}_{32}$Ge	—	^{72}Ge
—	—	—	—	—	—	$^{74}_{33}$As	—	—	—	—	—	—	—	^{73}Ge

H 50, T 9, S 2, S 6, S 8; [23] L 46. — ^{69}Zn*: [3, 4] L 46, K 6; [6] L 46; [7] K 6; [9] K 6; [19] T 9, L 46; [20] L 33, T 9, V 3, L 46, K 6, S 8; [21] T 9, L 46; [23] L 46. — ^{64}Ga: [6] B 61; [16] B 61. — ^{65}Ga: [6] L 49; [7] L 49; [9] V 2, D 32; [15] D 32; [18] V 3, L 49. — ^{66}Ga: [6] M 5; [8] M 3; [14] H 37, M 5; R 16, K 13, C 37a; [16] B 61. — ^{67}Ga: [6] M 7; [7] A 20, A 21, A 2; [9] V 3, A 21; [13] M 6, M 7; [16] D 28, B 61, V 3; [18] A 20, G 15, A 21, V 3. — ^{68}Ga: [6] M 5; [8] M 5; R 16; S 8; [14] R 14, H 37, R 16, M 5, K 13; [15] D 28; [16] D 28, B 61, W 14; [18] G 15, V 3; [19] S 11a; [24] C 13, P 28, S 2, S 6, S 8; [25] B 48, C 13, B 51, B 53. — ^{70}Ga: [6] M 7; [7] V 3; [8] M 6; M 7; S 8; [13] M 6, M 7; [16] D 28, B 61, V 3; [19] S 11a; [20] L 40; [21] A 27, S 2, L 40, S 6, S 8; [23] S 11a; [24] P 28, S 2, S 6; [25] B 48, C 13, B 51, B 53. — ^{72}Ga: [6] S 6; [8] L 49; S 8; [9] S 2; [19] S 11a; [20] L 40; [21] A 27, B 51, S 2, L 40, S 6, S 8; [23] S 11a. — (^{74})Ga: *) Assigned to ^{71}Ge* by S 27a. [6] S 11a; [8] S 11a; [19] S 11a; [23] S 6. — (^{69})Ge: [6] M 7; [14] M 7. — ^{71}Ge: [6] M 7; [8] S 27a; S 8, S 11a; M 7; [14] M 7; [17] L 49a, S 27a; [20] S 6, S 27a, S 11a; [21] S 6, S 8, S 11a; [22] S 11a; [24] S 6, S 8, S 11a. — (^{71})Ge*: **) Found by S 11a in the Ga-fraction and assigned to (^{74})Ga. [3, 4] S 27a; [6] S 27a; [7] S 27a; [9] S 27a; [17] L 49, S 27a; [20] S 27a.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
32	Ge	**42**	**74**	37.1	—	—	—	—	—	—
		43	75	—	[82 ± 2] *m*	β^-	1.2 ± 0.1; *1.10*	—	—	—
		44	**76**	6.5	—	—	—	—	—	—
		45	77	—	8 to 12 *h*	β^-	*1.92*	—	—	—
33	As	(39)	(72)	—	26 *h*	β^+	—	—	—	—
		40	73	—	[50 ± 3] *h*	β^+	0.6	—	—	—
		41	74	—	[16 ± 1] *d*	β^+, β^-	β^+: 0.65; *0.9*; β^-: *1.3*	—	—	—
		42	**75**	100	—	—	β^+: *0.70, 2.6*; β^-:	—	—	—
		43	76	—	[26.75 ± 0.15] *h*	β^+, β^-, *K*	0.8, 1.7, 2.71±0.14;	1.5, 2.16, 3.15	—	—
		44	77	—	[90 ± 10] *d*	β^-	0.5, 1.5, 3.24±0.20	—	—	—
		45	78	—	[65 ± 3] *m*	β^-	*1.4*	0.27	—	—
34	Se	**40**	**74**	0.9	—	—	—	—	—	—
		41	75	—	48 *d*	*K*	—	0.50	—	—
		42	**76**	9.5	—	—	—	—	—	—
		43	**77**	8.3	—	—	—	—	—	—
		44	**78**	24.0	—	—	—	—	—	—
		45	79	—	—	—	—	—	—	
		isomer		—	—	—	—	—	—	
		46	**80**	48.0	—	—	or —	—	—	or
		47	81	—	19 *m*	β^-	1.5	—	—	
		isomer		—	[57 ± 1] *m*	γ	—	0.098	—	
		48	**82**	9.3	—	—	—	—	—	—
		49	83	—	~30 *m*	β^-	—	—	—	—
35	Br	43	78	—	[6.4 ± 0.1] *m*	β^+	2.3	0.0458 ± 0.0004, 0.1077 ± 0.0009		
		44	**79**	50.6	—	—	—	—	—	—
		45	80	—	[18.5 ± 0.5] *m*	β^-	2.00 ± 0.10	< 0.5	—	—
		isomer		—	[4.54 ± 0.10] *h*	γ	—	0.0371 or 0.0253, 0.0489 ± 0.0004		
		46	**81**	49.4	—	—	—	—	—	—
		47	82	—	[33.9 ± 0.3] *h*	β^-	0.85 ± 0.20; 0.7; 0.45; singlet	0.65; none from 0.14 to 1.0; 3γ-qu. per decay	—	—
		48	83	—	[140 ± 10] *m*	β^-	1.05; 1.3	none	—	—
	1	>47	>82	—	[30 ± 5] *m*	β^-	—	—	—	—
	2	>47	>82	—	[3.0 ± 0.5] *m*	β^-	—	—	—	—
	3	>47	>82	—	[50 ± 10] *s*	β^-	—	—	—	—
36	Kr	**42**	**78**	0.35	—	—	—	—	77.945	1.6
		(43)	(79)	—	—	—	—	—	—	—
		44	**80**	2.01	—	—	or —	—	—	—
		45	81	—	[34.5 ± 1] *h* *)	β^+	0.4 ± 0.1	—	—	—
		46	**82**	11.52	—	—	—	—	81.938	1.3
		47	**83**	11.52	—	—	—	—	—	—
		isomer		—	113 *m*	γ	—	0.049	—	—

^{75}Ge: [6] S 11a; [8] S 11a; S 8, S 11a; [20] S 6, S 27a, S 11a; [21] S 6, S 8, S 11a; [22] S 27a, S 11a; [23] S 27a, S 11a; [24] P 28, S 6, S 27a, S 11a. — ^{77}Ge: [6] S 11a, S 27a; [8] S 8, S 11a; [20] S 6, S 27a, S 11a; [21] S 6, S 8, S 11a; [22] S 27a. — $^{(72)}$As: [6] V 6; [16] V 6. — ^{73}As: [6] S 6; [8] S 11a; [18] S 6, S 7, S 11a. — ^{74}As: [6] S 7; [7] C 62; [8] β^+: C 62; S 3, S 7; β^-: S 7; [16] D 32; [18] S 3, S 6, S 7, S 11a; [19] F 24; [24] P 28, C 62, S 3, S 7. — ^{76}As: [6] W 13; [7] H 24, S 21; [8] β^+: S 21; β^-: H 24, S 13, W 13; L 5, M 42; [9] H 24, S 21; [16] V 6; [19] F 24; [20] T 6, C 62, S 7, D 7, N 14; [21] A 27, F 6, B 59, H 24, N 20, C 62, W 17, S 21, S 7, W 13, L 5, M 42, S 46; [22] S 44, C 62, S 7; [23] S 7. — ^{77}As: [6] S 7; [18] S 3, S 6, S 7, S 11a. — ^{78}As: [6] S 44; [8] S 7; [9] S 7; [22] S 44, C 62, S 7; [23] S 7. — ^{75}Se: [6] D 32; [7] D 32; [9] D 32; [16] D 32. — ^{79,81}Se: [6] L 7; [8] L 7; [12] L 7; [20] S 43, S 44, L 7; [21] H 51, S 44, L 7; [23] L 7; [25] B 53. — ^{79,81}Se*: [3, 4] L 7; [6] S 44; [9] L 7; [20] S 44, L 7; [21] S 44, L 7; [23] S 44, L 7; [24] H 51; [25] B 53. — ^{83}Se: [6] L 7; [20] L 7; [21] L 7. — ^{76}Br: [6] S 44; [8] S 44; [9] V 3; [15] S 43, H 37, R 16, S 44; [16] B 61, V 1, V 3; [18] S 44; [24] P 28, H 51, C 13, S 44; [25] B 47, C 13, B 49, B 51, B 53, B 10. — ^{80}Br: [6] S 44;

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	Fission of		(α, n)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	$^{74}_{33}$As	—	—	$^{73}_{31}$Ga	$^{75}_{32}$Ge	$^{75}_{32}$Ge	—	($^{74}_{31}$Ga)	—	—	^{74}Ge
—	—	—	—	—	—	—	—	$^{74}_{32}$Ge	$^{74}_{32}$Ge	$^{73}_{34}$Se	$^{73}_{33}$As	$^{76}_{32}$Ge	—	^{75}Ge
—	—	—	—	$^{76}_{33}$As	—	$^{77}_{33}$As	($^{74}_{31}$)Ga	$^{77}_{32}$Ge	$^{77}_{32}$Ge	—	—	$^{75}_{32}$Ge	—	^{76}Ge
—	—	—	—	—	—	—	—	$^{76}_{32}$Ge	$^{76}_{32}$Ge	$^{80}_{34}$Se	—	—	—	^{77}Ge
—	—	—	—	($^{72}_{32}$)Ge	—	—	—	—	—	—	—	—	—	(^{72})As
—	—	—	—	—	—	$^{72}_{32}$Ge	—	—	—	—	—	—	—	^{73}As
—	—	—	—	$^{74}_{32}$Ge	—	$^{73}_{32}$Ge	$^{75}_{34}$Se	—	—	—	—	$^{75}_{33}$As	—	^{74}As
—	—	—	$^{78}_{35}$Br	$^{75}_{34}$Se	—	—	—	$^{75}_{33}$As	$^{75}_{33}$As	—	$^{75}_{32}$Ge	$^{74}_{33}$As	—	^{75}As
—	—	—	—	$^{76}_{32}$Ge	—	—	$^{78}_{34}$Se	$^{75}_{33}$As	$^{75}_{33}$As	$^{79}_{35}$Br	$^{76}_{34}$Se	—	—	^{76}As
—	—	—	—	—	—	$^{76}_{32}$Ge	—	—	—	—	—	—	—	^{77}As
—	—	—	—	—	—	—	—	—	—	$^{81}_{35}$Br	$^{78}_{34}$Se	—	—	^{78}As
—	—	—	—	—	—	—	—	—	—	$^{71}_{32}$Ge	—	—	—	^{74}Se
—	—	—	—	$^{75}_{33}$As	—	—	—	—	—	—	—	—	—	^{75}Se
—	—	—	($^{79}_{36}$)Kr	—	—	—	$^{74}_{33}$As	—	—	—	$^{76}_{33}$As	—	—	^{76}Se
—	—	—	or	—	—	$^{78}_{35}$Br	—	—	—	—	—	—	—	^{77}Se
—	—	—	$^{81}_{36}$Kr	$^{78}_{35}$Br	—	—	$^{76}_{33}$As	$^{79}_{34}$Se	$^{79}_{34}$Se	$^{75}_{32}$Ge	$^{78}_{33}$As	—	—	^{78}Se
$^{79}_{34}$Se*	—	—	—	—	—	—	—	$^{76}_{34}$Se + or	$^{78}_{34}$Se + or	—	$^{79}_{31}$Br	—	$^{80}_{34}$Se	^{79}Se
$^{79}_{34}$Se	—	—	—	—	—	—	(α, p)	$^{78}_{34}$Se +	$^{78}_{34}$Se +	—	$^{79}_{35}$Br	$^{80}_{34}$Se	$^{80}_{34}$Se	^{79}Se*
—	—	—	$^{83}_{36}$Kr*	$^{80}_{35}$Br	—	—	($^{83}_{35}$Br)	$^{81}_{34}$Se	$^{81}_{34}$Se	$^{77}_{32}$Ge or	—	$^{79}_{34}$Se* or	$^{79}_{34}$Se	^{80}Se
$^{81}_{34}$Se*	—	—	—	—	—	—	—	$^{80}_{34}$Se	$^{80}_{34}$Se	—	$^{81}_{35}$Br	or	$^{82}_{34}$Se or	^{81}Se
$^{81}_{34}$Se	—	—	—	—	—	—	—	$^{80}_{34}$Se	$^{80}_{34}$Se	—	$^{81}_{35}$Br	$^{82}_{34}$Se or	$^{82}_{34}$Se or	^{81}Se*
—	—	—	($^{85}_{36}$Kr)	$^{83}_{35}$Br	$^{83}_{35}$Br	$^{83}_{35}$Br	—	$^{83}_{34}$Se	$^{83}_{34}$Se	—	—	$^{81}_{34}$Se*	$^{81}_{34}$Se	^{82}Se
$^{83}_{35}$Br	—	—	—	—	—	—	—	$^{82}_{34}$Se	$^{82}_{34}$Se	—	—	—	—	^{83}Se
—	—	(p, γ)	$^{75}_{33}$As	$^{78}_{34}$Se	—	$^{77}_{34}$Se	—	—	—	—	—	$^{78}_{35}$Br	$^{78}_{35}$Br	^{78}Br
—	—	($^{7}_{36}$Kr)	$^{82}_{37}$Rb	$^{7}_{36}$Kr ($^{79}_{36}$)Kr	—	—	—	$^{80}_{35}$Br	$^{80}_{35}$Br	$^{76}_{33}$As	$^{79}_{34}$Se	$^{78}_{35}$Br	$^{78}_{35}$Br	^{79}Br
$^{80}_{35}$Br*	—	—	—	$^{80}_{34}$Se	or	—	—	$^{79}_{35}$Br	$^{79}_{35}$Br	—	or	$^{81}_{35}$Br	$^{81}_{35}$Br	^{80}Br
$^{80}_{35}$Br	—	—	—	$^{80}_{34}$Se		—	—	$^{79}_{35}$Br	$^{79}_{35}$Br	—	$^{81}_{34}$Se	$^{81}_{35}$Br	$^{81}_{35}$Br	^{80}Br*
—	—	($^{7}_{36}$Kr)	$^{84}_{37}$Rb	$^{7}_{36}$Kr $^{81}_{36}$Kr		—	—	$^{82}_{35}$Br	$^{82}_{35}$Br	$^{78}_{33}$As		$^{80}_{35}$Br	$^{80}_{35}$Br	^{81}Br
—	—	—	—	$^{82}_{34}$Se	$^{82}_{34}$Se	—	—	$^{81}_{35}$Br	$^{81}_{35}$Br	$^{85}_{37}$Rb		—	—	^{82}Br
$^{82}_{34}$Se $^{82}_{35}$Kr*	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	$^{82}_{34}$Se	($^{80}_{34}$Se)	—	—	—	—	—	—	^{83}Br
—	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	$>^{82}$Br^{1}
	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	$>^{82}$Br^{2}
	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	$>^{82}$Br^{3}
—	—	—	—	—	—	—	(d, d)	($^{79}_{36}$)Kr	—	—	—	—	—	^{79}Kr
—	—	—	($^{79}_{34}$)Se	($^{79}_{35}$)Br	—	—	—	($^{79}_{36}$)Kr or	or	—	—	—	—	(^{79})Kr
—	—	—	or	or	—	—	or	$^{81}_{36}$Kr	—	—	—	—	—	^{80}Kr
—	—	—	$^{78}_{34}$Se	$^{81}_{35}$Br	—	—	—	$^{80}_{36}$Kr	—	—	—	—	—	^{81}Kr
—	—	—	—	—	—	—	—	$^{83}_{36}$Kr*	—	—	—	—	—	^{82}Kr
—	—	—	—	—	—	$^{84}_{37}$Rb	$^{83}_{36}$Kr*	—	or	—	—	—	—	^{83}Kr
$^{83}_{35}$Br $^{83}_{36}$Kr	$^{235}_{92}$U	$^{232}_{90}$Th	$^{80}_{34}$Se	—	—	$^{84}_{37}$Rb	$^{83}_{36}$Kr or	$^{83}_{35}$Kr	—	—	—	—	—	^{83}Kr*

[8] A 8; [9] S 44, B 61; [12] S 30, D 19; [16] D 28, B 61, V 1; [22] S 43, S 44; [21] A 27, A 12, S 43, E 7, E 8, A 8, S 30, D 19, C 49; [24] H 51, S 43, S 45; [25] B 46, C 13, B 49, B 51, B 53, B 10. — ^{80}Br*: [3, 4] B 49, S 43; [6] S 44; [7] S 30, D 19; [9] V 3; [16] D 28, B 61, V 1, V 3; [20] S 43, S 44; [21] A 27, A 12, S 43, E 7, E 8, A 8, S 30, D 19, R 29, G 18, C 49; [24] S 43, S 45; [25] B 49, C 13, B 51, B 53, B 10. — ^{82}Br: [6] S 44; [8] A 8; B 61; D 18c; D 27a; [9] K 29; D 18c; D 27a; [16] D 28, B 61, V 1; [17] S 43, S 44, L 7; [20] S 43, S 44; [21] K 29, A 12, J 5, S 43, E 7, E 8, C 49; [22] S 43. — ^{83}Br: [6] H 19a; [8] L 7; S 44; [9] S 44; [12] S 44, L 7; [13] H 11, H 13, H 14, L 7, H 19a; [14] L 7, P 11; [18] S 43, S 44; [19] C 16. — $>^{82}$Br^{1}: [6] H 19a; [13] D 23, H 11, H 13, H 14, H 19a; [14] P 11. — $>^{82}$Br^{2}: [6] H 19a; [13] H 19a. — $>^{82}$Br^{3}: [6] H 19a; [13] H 19a. — $^{(79),81}$Kr: [6] C 49; *) after S 44: $T = [18 \pm 2]\ h$; [8] C 49; [15] C 16; [16] B 8, C 49; [20] S 44, C 16. — ^{83}Kr*: [3, 4] L 7; [6] L 7; [7] L 7; [9] L 7; [12] L 7; [13] L 7; [14] L 7; [15] K 4, C 16; [19] or [20] C 16.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
36	Kr	**48**	**84**	57.13	—	—	—	—	83.939	1.3
		(49)	(85)	—	1 to 2 *m*	—	—	—	—	—
		50	**86**	17.47	—	—	—	—	85.939	1.4
		51	87	—	4.0 *h*	β^-	—	—	—	—
		52	88	—	[175 ± 10] *m*	β^-	—	—	—	—
		53	89	—	2.5 to 3 *m*	β^-	—	—	—	—
		(55)	(91)	—	very short	β^-	—	—	—	—
		>55	>91	—		β^-	—	—	—	—
		?	?*)	—	[55 ± 2] *s*	(γ)	—	0.127	—	—
		?	?*)	—	[13 ± 2] *s*	(γ)	—	0.187	—	—
37	**Rb**	45	82	—	20 *m***)	—	or —	—	—	—
		47	84	—	6.5 *h***)	—	—	—	—	—
		48	**85**	72.8	—	—	—	—	—	—
		49	86	—	[18 ± 1] *d*	β^-	1.56 ± 0.05	—	—	—
		50	*87*	27.2	$6.3 \cdot 10^{10}$ *a*	β^-	0.132 ± 0.02	—	—	—
		51	88	—	[17.8 ± 0.2] *m*	β^-	4.6	—	—	—
		52	89	—	[15.4 ± 0.2] *m*	β^-	3.8	—	—	—
		(54)	(91)	—	80 *s*	β^-	—	—	—	—
		>54	>91	—	?	β^-	—	—	—	—
38	**Sr**	**46**	**84**	0.56	—	—	—	—	—	—
		47	85	—	66 *d*	*K*	—	0.8	—	—
		isomer		—	70 *m*	γ	—	0.17	—	—
		48	**86**	9.86	—	—	—	—	—	—
		49	**87**	7.02	—	—	—	—	—	—
		isomer		—	[2.75 ± 0.1] *h*	γ	—	0.37	—	—
		50	**88**	82.56	—	—	—	—	—	—
		51	89	—	[55 ± 5] *d*	β^-	1.50	none	—	—
		52	90	—	several *a*	β^-	—	—	—	—
		(53)	(91)	—	2.7 *h*	β^-	—	—	—	—
		>53	>91	—	8.5 *h*	β^-	—	—	—	—
		?	?	—	7 *m*	β^-	—	—	—	—
39	**Y**	47	86	—	—	—	—	—	—	—
		48	87	—	[80 ± 3] *h*	*K*	or —	(none)	—	—
		isomer		—	[14 ± 2] *h*	γ	—	~0.5	—	—
	1	49	88	—	[105 ± 5] *d*	*K*	—	1.87 ± 0.05; ~2.0	—	—
	2	49	88	—	[2.0 ± 0.2] *h*	β^+	*1.2*	—	—	—
		50	**89**	100	—	—	—	—	—	—
		51	90	—	[60.5 ± 2.0] *h*	β^-	*0.90, 2.11; 2.6*; 2.4	—	—	—
		(52)	(91)	—	3.5 *h*	β^-	~2.0; ~3.6	—	—	—
		>52	>91	—	50 *m*	β^-	1.4	—	—	—
		isomer		—	[57 ± 3] *d*	β^-	—	—	—	—

$^{(85)}$Kr: [6] K 12; [15] K 12, (C 16); [20] *) compare ((d, p) Kr) $T = [74 \pm 2]$ *m*, β^-: S 44. — ^{87}Kr: [6] C 16; [7] S 44; [20] S 44, C 16. — ^{88}Kr: [6] G 10; [13] H 52, H 11, H 13, H 14, S 28, G 10, H 19; [14] A 33, L 6, H 11, H 13. — ^{89}Kr: [6] S 28; [13] H 15, S 28, G 10, H 19. — $^{(91)}$Kr: [6] H 15; [13] H 52, H 15, H 19, G 12a; [14] H 16. — $>^{91}$Kr: [13] H 18, G 12a. — ^{7}Kr^{1}: [4] *) $79 < A < 82$: C 49; [6] C 49; [7] C 49; [9] C 49; [14] or [16] C 49. — ^{7}Kr^{2}: [4] $79 < A < 82$: C 49; [6] C 49; [7] C 49; [9] C 49; [14] or [16] C 49. — ^{82}Rb: [6] H 21; [15] H 21. — ^{84}Rb: [6] H 21; [15] H 21; [18] H 21. — **) compare ($^{79, 81}$Br (α, n) $^{82, 84}$Rb) $T = 1{,}5$ *m*, β^+ and $T = 9{,}8$ *m* (β^+): R 16; also Kr $(d, ?)$ Rb $T =$ 200 *h* and $T = 42$ *m*: H 21. — ^{86}Rb: [6] S 44; [8] H 31b; [19] H 31b; [21] S 44, S 22. — ^{87}Rb: [6] S 56; [8] L 30, O 10a. — ^{88}Rb: [6] G 10; [8] G 10; [12] H 52, A 33, H 11, L 6, S 28, G 10, H 19; [13] H 52, H 11, H 13, H 14, G 19, S 28, G 10, H 19; [13/14] G 19; [14] A 33, L 6, H 11, H 13, G 19; [21] F 14, S 44, S 22; [23] P 28, R 7. — ^{89}Rb: [6] G 10; [8] G 10; [12] H 15, S 28, G 10, H 19; [13] H 15, S 28, G 10, H 19. — $^{(91)}$Rb: [6] H 15; [12] H 52, H 15, H 16, H 19, G 12a; [13] H 52, H 15, H 19, G 12a; [14] H 16. — $>^{91}$Rb: [12] H 18, G 12a; [13] H 18, G 12a. — ^{85}Sr: [6] D 31; [7] D 31; [9] D 31; [16] D 30, D 31. — ^{85}Sr*: [3, 4] D 31; [6] D 31; [7] D 31; [9] D 31; [16] D 31. — ^{87}Sr: [12] H 6, M 9. — ^{87}Sr*:

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Table IV

Radioactive Decay	Fission of		(α, n)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{84}Kr
—	—	—	($^{82}_{34}$Se)	—	—	—	—	*)	—	—	—	—	—	(^{85})Kr
—	—	—	—	—	—	—	—	$^{87}_{36}$Kr	—	—	—	—	—	^{86}Kr
—	—	—	—	—	—	—	—	$^{86}_{36}$Kr	—	—	—	—	—	^{87}Kr
$^{88}_{37}$Rb	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{88}Kr
$^{89}_{37}$Rb	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	^{89}Kr
(^{91})Rb	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	(^{91})Kr
>$^{91}_{37}$Rb	$^{235}_{92}$U	(p, γ)	—	—	—	—	—	—	—	—	—	—	—	>^{91}Kr
—	—	($^{79,81}_{35}$Br)	— or	— $^{79,81}_{35}$Br	—	—	—	—	—	—	—	—	—	$^{?}$Kr^{1}
—	—	($^{79,81}_{35}$Br)	— or	— $^{79,81}_{35}$Br	—	—	—	—	—	—	—	—	—	$^{?}$Kr^{2}
—	—	—	$^{79}_{35}$Br	—	—	—	—	—	—	—	—	—	—	^{82}Rb
—	—	—	$^{81}_{35}$Br	—	—	$^{82}_{36}$Kr	—	—	—	—	—	—	—	^{84}Rb
—	—	—	—	$^{85}_{38}$Sr	—	—	—	—	$^{84}_{37}$Rb	$^{82}_{35}$Br	—	—	—	^{85}Rb
—	—	—	—	—	—	—	$^{82}_{38}$Sr	—	$^{85}_{37}$Rb	—	—	—	—	^{86}Rb
$^{87}_{37}$Sr	—	—	—	$^{87}_{38}$Sr*	—	—	—	—	$^{88}_{37}$Rb	—	—	—	—	^{87}Rb
$^{88}_{36}$Kr	$^{235}_{92}$U, $^{231}_{91}$Pa,	$^{232}_{90}$Th	—	—	—	—	—	—	$^{87}_{37}$Rb	—	$^{88}_{38}$Sr	—	—	^{88}Rb
$^{89}_{36}$Kr $^{89}_{38}$Sr	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	^{89}Rb
($^{91}_{36}$)Kr ($^{91}_{38}$Sr)	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	(^{91})Rb
>$^{91}_{36}$Kr >$^{91}_{38}$Sr	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{91}Rb
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{84}Sr
—	—	—	—	$^{86}_{37}$Rb	—	—	—	—	—	—	—	—	—	^{85}Sr
—	—	—	—	$^{85}_{37}$Rb	—	—	—	—	—	—	—	—	—	^{85}Sr*
	—	—	(p, p)	$^{86}_{39}$Y	— $^{86}_{39}$Y	$^{87}_{39}$Y	—	$^{87}_{38}$Sr*	$^{87}_{38}$Sr*	—	—	(n, n)	—	^{86}Sr
$^{87}_{37}$Rb	—	—	($^{87}_{38}$Sr*)	$^{87}_{39}$Y	—	or $^{88}_{39}$Y^{2}	—	—	—	—	—	$^{87}_{38}$Sr*	—	^{87}Sr
$^{87}_{39}$Y	—	—	($^{87}_{38}$Sr)	$^{87}_{37}$Rb	—		—	$^{86}_{38}$Sr	$^{86}_{38}$Sr	$^{90}_{40}$Zr	—	$^{87}_{38}$Sr	—	^{87}Sr*
—	—	—	—	$^{86}_{39}$Y^{2}, $^{88}_{39}$Y^{1}	— $^{88}_{39}$Y^{1}		$^{86}_{37}$Rb	$^{88}_{38}$Sr	$^{88}_{38}$Sr	—	$^{88}_{37}$Rb	—	—	^{88}Sr
$^{89}_{37}$Rb	$^{235}_{92}$U	—	—	—	—	—	—	$^{88}_{38}$Sr	$^{88}_{38}$Sr	($^{92}_{40}$Zr)	$^{89}_{39}$Y	—	—	^{89}Sr
$^{90}_{39}$Y	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	^{90}Sr
($^{91}_{37}$Rb) ($^{91}_{39}$Y	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	(^{91})Sr
>$^{91}_{37}$Rb >$^{91}_{39}$Y	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	>^{91}Sr
—	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	$^{?}$Sr
—	—	—	—	$^{86}_{38}$Sr	$^{86}_{38}$Sr	—	—	—	—	—	—	—	—	^{86}Y
$^{87}_{38}$Sr*	—	—	or	$^{87}_{38}$Sr	or	$^{86}_{38}$Sr	—	—	—	—	—	—	—	^{87}Y
—	—	—		$^{87}_{38}$Sr		$^{86}_{38}$Sr	—	—	—	—	—	—	—	^{87}Y*
—	—	—		$^{88}_{38}$Sr	$^{88}_{38}$Sr	—	—	—	—	—	—	—	—	^{88}Y^{1}
—	—	—	—	$^{88}_{38}$Sr	—	$^{87}_{38}$Sr	—	—	—	—	—	$^{89}_{39}$Y	—	^{88}Y^{2}
—	—	—	—	$^{89}_{40}$Zr	—	—	—	$^{90}_{39}$Zr	$^{90}_{39}$Zr	—	$^{89}_{38}$Sr	$^{89}_{39}$Y^{2}	—	^{89}Y
$^{90}_{38}$Sr	$^{235}_{92}$U	—	—	—	—	—	$^{93}_{40}$Zr	$^{89}_{39}$Y	$^{89}_{39}$Y	$^{93}_{41}$Nb	$^{90}_{40}$Zr	—	—	^{90}Y
($^{91}_{38}$Sr	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	($^{91}_{40}$Zr	—	—	(^{91})Y
>$^{91}_{38}$Sr	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{91}Y
>$^{91}_{38}$Sr	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{91}Y*

[3, 4] D 30, D 31; [6] D 31; [7] D 30, D 31; [9] D 30, D 31; [12] D 30, D 31; [15] D 31; [16] D 30, D 31; [20] S 53, S 54, D 30, D 31; [21] P 28, S 53, S 54, D 30, R 6, R 7, D 31; [22] S 4, S 10; [24] R 6, R 7, D 31. — ^{89}Sr: [6] S 54; [8] S 54; [9] S 54; [12] H 15, S 28, G 10, H 19; [13] L 32, H 13, H 14, H 15, G 10, H 19; [20] S 53, S 54, H 31 b; [21] S 53, S 54; [22] S 10; [23] S 4. — ^{90}Sr: [6] H 19d; [13] H 19d, G 12b. — (^{91})Sr: [6] G 12a; [12] G 12a; [13] G 12a. — >^{91}Sr: [6] G 12a; [12] H 15, H 16, H 19, G 12a; [13] L 32, H 15, H 19, G 12a; [14] H16. — $^{?}$Sr: [6] L 32; [13] L 32. — ^{87}Y: [6] D 31; [7] D 30, D 31; [9] D 31; [16] D 30, D 31; [18] S 54, D 30, D 31. — ^{87}Y*: [3, 4] S 54, D 31; [6] S 54; [7] D 31; [9] D 31; [16] D 31; [18] S 54, D 31. — ^{86}, ^{88}Y^{1}: [6] D 31; [7] D 31; [9] S 21a; D 31; [16] D 31; [17] P 3a, H 31b, S 21a. — ^{88}Y^{2}: [6] S 54; [8] S 53; [16] D 31; [18] S 53, S 54, D 31; [24] P 28, S 53. — ^{90}Y: [6] S 53; [8] S 11; S 53; G 12b; [12] H 19d, G 12b; [13] H 19d, G 12b; [19] S 4, S 10; [20] S 53; [21] A 27, R 3, H 45, P 28, S 53, S 4, S 11; [22] S 5, S 11; [23] S 4, S 10. — (^{91})Y: [6] G 12a; [8] S 10; G 12a; [12] L 32, H 15, H 16, H 19, G 12a; [13] L 32, H 13, H 14, H 15, G 12a; [14] H 16; [23] S 4, S 10. — >^{91}Y: [6] G 12a; [8] G 12a; [12] G 12a; [13] G 12a. — >^{91}Y*: [3, 4] G 12a; [6] H 18; [12] H 18, G 12a; [13] H 18, G 12a.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
40	**Zr**	49	89	—	[78 ± 1] *h*	β^+	*0.57, 1.05*; 1.0	none	—	—
		isomer		—	4.5 *m*	γ	—	—	—	—
		50	**90**	48	—	—	—	—	—	—
		51	**91**	11.5	—	—	—	—	—	—
		52	**92**	22	—	—	—	—	—	—
		53	93	—	[63 ± 5] *d*	β^-	*0.20, 0.48*; 0.25	—	—	—
		54	**94**	17	—	—	—	—	—	—
		55	95	—	[17.0 ± 0.2] *h*	β^-	*1.17*; 1.2; ~1	—	—	—
		56	**96**	1.5	—	—	—	—	—	—
		(57)	(97)	—	[6 ± 1] *m*	β^-	~1.9	—	—	—
		?	?	—	[26 ± 2] *d*	β^-	~0.25	—	—	—
41	**Nb**	51	92	—	[11 ± 1] *d*	β^-	*1.38*	—	—	—
		52	**93**	100	—	—	—	—	—	—
		isomer		—	[55 ± 5] *d*	γ	—	0.20	—	—
		53	94	—	[6.6 ± 0.3] *m*	β^-	~1.4	0.4	—	—
		54	95	—	[75 ± 3] *m*	β^-	1.8; ~1	—	—	—
42	**Mo**	49	91	—	[17 ± 1] *m*	β^+	2.65	—	—	—
		50	**92**	14.9	—	—	or —	—	—	—
		51	93	—	—	—	—	—	—	—
		52	**94**	9.40	—	—	—	—	93.945	4.2
		53	**95**	16.1	—	—	—	—	94.945	4.3
		54	**96**	16.6	—	—	—	—	95.946	4.3
		55	**97**	9.65	—	—	—	—	96.945	2.9
		56	**98**	24.1	—	—	—	—	97.944	3.0
		57	99	—	[67 ± 2] *h*	β^-	*1.03, 1.44*; 1.5	0.4	—	—
		58	**100**	9.25	—	—	—	—	99.939	3.0
		59	101	—	[14.6 ± 0.3] *m*	β^-	*1.78*; 1.9	—	—	—
		> 59	>101	—	12 *m*	β^-	—	—	—	—
43	—	53	96	—	[2.7 ± 0.4] *h*	(β^+)	—	—	—	—
		56	99	—	> 40 *a*	—	—	—	—	—
		isomer		—	[6.6 ± 0.4] *h*	γ	—	0.136, 0.18	—	—
		58	101	—	[14.0 ± 0.3] *m*	β^-	*1.14*; 1.2	—	—	—
		< 58	<101	—	[110 ± 10] *h*	(K, β^-)	0.6	0.05, 0.5	—	—
	1	< 59	<102	—	90 *d*	(K)	—	—	—	—
	2	< 59	<102	—	62 *d*	(K)	—	—	—	—
	3	< 59	<102	—	~2 *d*	K	—	—	—	—
		> 58	>101	—	very short?	—	—	—	—	—
44	**Ru**	(51)	(95)	—	20 *m*	—	—	—	—	—
		52	**96**	(5)	—	—	—	—	95.945	2.9
		54	**98**	?	—	—	—	—	—	—
		55	**99**	(12)	—	—	—	—	98.944	2.9
		56	**100**	(14)	—	—	—	—	—	—
		57	**101**	(22)	—	—	—	—	—	—
		58	**102**	(30)	—	—	—	—	—	—

^{89}Zr: [6] D 31; [8] S 10; S 4, S 10, D 31; [9] D 31; [16] D 31; [22] S 10; [24] S 4, S 10 — ^{89}Zr*: [3, 4] D 31; [6] D 31; [7] D 31; [16] D 31. — ^{90}Zr: [6] S 10; [8] S 10; S 10; [20] S 4, S 10; [21] S 4, S 10, [22] S 10; [24] S 4, S 10. — ^{92}Zr: [6] G 20; [8] S 10; S 10; G 20; [13] G 20, H 18, A 31a; [14] H 19b; [21] H 42, S 4, S 10; [22] S 10. — $^{(97)}$Zr: [6] S 10; [8] S 10; [21] S 10. — ?Zr: [6] H 18; [8] G 20; [13] H 18, G 20; [14] H 19b. — ^{92}Nb: [6] S 5; [8] S 11; [23] S 10; [24] S 5, S 11. — ^{92}Nb*: [3, 4] S 10; [6] S 10; [7] S 10; [9] S 10; [12] S 10; [18] S 10. — ^{94}Nb: [6] S 11; [8] S 11; [9] S 11; [21] S 5, S 11. — ^{95}Nb: [6] G 20; [8] S 10; G 20; [12] S 10, G 20, H 19b; [13] G 20; [14] H 19b; [23] S 10. — $^{91, 92}$Mo: [6] B 51, S 4; [8] S 10; [24] H 51, P 28, S 4; [25] B 48, B 51, B 53. — ^{99}Mo: [6] S 26; [8] S 10; S 26; [9] S 26; [13] H 10, H 13, H 14, S 33, H 18; [14] H 12, H 13, S 33;

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	Fission of		(α, n)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	[illegible]	—	—	—	—	—	$^{92}_{42}$Mo	—	$^{90}_{40}$Zr	—	^{89}Zr
—	—	—	—	[illegible]	—	—	—	—	—	—	—	—	—	^{89}Zr*
—	—	—	—	—	—	—	—	—	—	$^{87}_{38}$Sr*	$^{90}_{39}$Y	$^{89}_{40}$Zr	—	^{90}Zr
—	—	—	—	—	—	—	—	—	—	—	$^{(91)}_{39}$Y	—	—	^{91}Zr
—	—	—	—	—	—	($^{93}_{41}$Nb*)	$^{90}_{39}$Y	$^{93}_{40}$Zr	$^{93}_{40}$Zr	($^{89}_{38}$Sr)	—	—	—	^{92}Zr
$^{93}_{41}$Nb*	—	—	—	—	—	—	—	$^{92}_{40}$Zr	$^{92}_{40}$Zr	($^{96}_{42}$Mo)	—	$^{94}_{40}$Zr	—	^{92}Zr
—	—	—	—	—	—	—	—	—	$^{95}_{40}$Zr	—	—	$^{93}_{40}$Zr	—	^{94}Zr
$^{95}_{41}$Nb	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	$^{94}_{40}$Zr	$^{95}_{42}$Mo	—	—	—	^{95}Zr
—	—	—	—	—	—	—	—	—	$^{(97)}_{40}$Zr	—	—	—	—	^{96}Zr
—	—	—	—	—	—	—	—	—	$^{(96)}_{40}$Zr	—	—	—	—	$^{(97)}$Zr
—	$^{233}_{92}$U	($^{232}_{90}$Th)	—	—	—	—	—	—	—	—	—	—	—	Zr
—	—	—	—	—	—	—	—	—	—	—	$^{92}_{42}$Mo	$^{92}_{41}$Nb	—	^{92}Nb
—	—	—	^{96}43	—	—	—	—	—	$^{94}_{41}$Nb	$^{90}_{39}$Y	—	$^{92}_{41}$Nb	—	^{93}Nb
$^{93}_{40}$Zr	—	—	—	—	—	($^{92}_{40}$Zr)	—	—	—	—	—	—	—	^{93}Nb*
—	—	—	—	—	—	—	—	—	$^{93}_{41}$Nb	—	—	—	—	^{94}Nb
$^{95}_{40}$Zr	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	$^{95}_{42}$Mo	—	—	^{95}Nb
—	—	—	—	—	—	—	—	—	—	—	—	$^{92}_{42}$Mo	$^{92}_{42}$Mo	^{91}Mo
—	—	—	—	—	—	—	—	—	—	$^{89}_{40}$Zr	$^{93}_{41}$Nb	$^{91}_{42}$Mo or $^{94}_{42}$Mo	$^{91}_{42}$Mo or $^{94}_{42}$Mo	^{92}Mo
—	—	—	—	—	—	—	—	—	—	—	—			^{93}Mo
—	—	—	—	—	—	—	—	—	—	—	—	$^{93}_{42}$Mo	$^{93}_{42}$Mo	^{94}Mo
—	—	—	—	—	—	^{96}43	—	—	—	—	$^{95}_{41}$Nb	—	—	^{95}Mo
—	—	—	—	^{96}43	—	—	—	—	—	($^{93}_{40}$Zr)	—	—	—	^{96}Mo
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{97}Mo
—	—	—	—	—	—	—	—	$^{99}_{42}$Mo	$^{99}_{42}$Mo	$^{95}_{40}$Zr	—	—	—	^{98}Mo
^{99}43*	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	$^{98}_{42}$Mo	$^{98}_{42}$Mo	—	—	$^{100}_{42}$Mo	—	^{99}Mo
—	—	—	—	—	—	—	—	—	$^{101}_{42}$Mo	—	—	$^{99}_{42}$Mo	—	^{100}Mo
^{101}43	$^{235}_{92}$U	—	—	—	—	—	—	—	$^{100}_{42}$Mo	—	—	—	—	^{101}Mo
(>^{101}43)	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{101}Mo
—	—	—	$^{93}_{41}$Nb	[illegible]	—	$^{98}_{42}$Mo	—	—	—	—	—	—	—	^{96}43
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{99}43
$^{99}_{42}$Mo	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{99}43*
$^{101}_{42}$Mo	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	^{101}43
—	—	—	—	[illegible]	—	—	—	—	—	—	—	—	—	<^{101}43
—	—	—	—	—	—	$^{?}_{42}$Mo	—	—	—	—	—	—	—	<^{102}43^{1}
—	—	—	—	—	—	$^{?}_{42}$Mo	—	—	—	—	—	—	—	<^{102}43^{2}
—	—	—	—	—	—	$^{?}_{42}$Mo	—	—	—	—	—	—	—	<^{102}43^{3}
(>$^{101}_{42}$Mo)	($^{235}_{92}$U)	—	—	—	—	—	—	—	—	—	—	—	—	>^{101}43
—	—	—	—	—	—	—	—	—	—	—	—	$^{(96)}_{44}$Ru	—	$^{(95)}$Ru
—	—	—	—	—	—	—	—	—	—	—	—	$^{(95)}_{44}$Ru	—	^{96}Ru
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{98}Ru
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{99}Ru
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{100}Ru
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{101}Ru
—	—	—	—	—	—	—	—	$^{102}_{44}$Ru	$^{102}_{44}$Ru	—	—	—	—	^{102}Ru

[20] S 26; [21] A 27, M 16, S 26, S 4, S 10, M 11a; [24] S 4, S 10, M 11a. — ^{101}Mo: [6] M 11a; [8] S 9, S 10; S 10; [13] H 18, H 19c; [21] A 27, M 16, H 51, S 4, S 9, M 11a. — >^{101}Mo: [6] H 19c; [13] H 19c. — ^{96}43: [6] D 18; [15] K 12; [16] D 18; [18] S 26. — ^{99}43: [6] S 26. — ^{99}43*: [6] S 26; [7] S 26; [9] S 26; [12] K 1, S 26, S 33, S 10; [13] S 33; [14] S 33. — ^{101}43: [6] M 11a; [8] S 9, S 10; S 10; [12] S 9, S 10, M 11a, H 19c; [13] H 19c. — <^{101}43: [6] E 11; [7] E 11, E 12; [8] E 11; [9] E 12; [16] E 11. — <^{102}43^{1}: [6] C 2; [7] C 1, C 2; [18] C 1, C 2. — <^{102}43^{2}: [6] C 2; [7] C 1, C 2; [18] C 1, C 2. — <^{102}43^{3}: [6] S 26; [7] S 26; [18] S 26. — >^{101}43: [6] H 19c; [12] H 19c; [13] H 19c. — $^{(95)}$Ru: [6] V 11; [24] P 28, V 11.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
44	Ru	59	103	—	4 *h*	β^-	—	—	—	—
		60	**104**	(17)	—	—	—	—	—	—
		61	105	—	20 *h*	β^-	—	—	—	—
		> 61	> 105	—	4 *h*	β^-	—	—	—	—
45	**Rh**	**58**	**103**	100	—	—	—	—	102.949	5.2
		59	104	—	[41.8 ± 0.7] *s*	β^-	2.46 ± 0.10; 2.3; *2.74*; *2.8*	—	—	—
		isomer		—	[4.34 ± 0.06] *m*	γ	—	~0.080	—	—
		60	105	—	45 *d*	β^-	—	—	—	—
		> 60	> 105	—	34 *h*	β^-	0.5	—	—	—
46	**Pd**	**56**	**102**	0.8	—	—	—	—	—	—
		58	**104**	9.3	—	—	—	—	—	—
		59	**105**	22.6	—	—	—	—	—	—
		60	**106**	27.2	—	—	—	—	105.946	4.3
		61	107	—	—	—	—	—	—	—
		62	**108**	26.8	—	—	or —	—	—	—
		63	109	—	13 *h*	β^-	1.03	—	—	—
		64	**110**	13.5	—	—	—	—	109.944	4.4
		65	111	—	26 *m*	β^-	—	—	—	—
		66	112	—	17 *h*	β^-	—	—	—	—
47	**Ag**	(55)	(102)	—	[73 ± 10] *m*	—	—	—	—	—
		(57)	(104)	—	[16.3 ± 0.7] *m*	—	—	—	—	—
		(58)	(105)	—	[45 ± 5] *d*	*K*	—	0.29, 0.42, 0.51, 0.62	—	—
		59	106	—	[25.0 ± 0.5] *m*	β^+	2.04 ± 0.05; 1.9; 1.90	none	—	—
		isomer		—	[8.2 ± 0.2] *d*	*K*	—	0.69, 1.06; 0.28, 0.68, 0.95	—	—
		60	**107**	52.5	—	—	—	—	106.950	3.2
		isomer		—	[40 ± 2] *s*	γ	—	0.0935; 0.0926 ± 0.0008	—	—
		61	108	—	[2.44 ± 0.06] *m*	β^-	or 2.06; *2.8*	—	—	—
		(isomer)		—	[225 ± 20] *d*	β^-	—	—	—	—
		62	**109**	47.5	—	—	—	—	108.949	3.3
		isomer		—	—	—	—	—	—	—
		63	110	—	[24.17 ± 0.5] *s*	β^-	or *2.8*	—	—	—
		(isomer)		—	—	—	—	—	—	—
		64	111	—	7.5 *d*	β^-	0.80; 0.8	none	—	—
		65	112	—	3.2 *h*	β^-	2.2; 2	—	—	—
48	**Cd**	**58**	**106**	1.4	—	—	—	—	—	—
	1	59	107	—	6.7 *h*	*K*	—	0.53	—	—
	2	59	107	—	~90 *d*	*K*	—	—	—	—
		60	**108**	1.0	—	—	or —	—	—	—
	1	61	109	—	—	—	—	—	—	—
	2	61	109	—	—	—	—	—	—	—
		(61)	(109)	—	33 *m*	β^+	—	—	—	—
		62	**110**	12.8	—	—	—	—	—	—

^{103}Ru: [6] V 11; [20] L 33; [21] V 8, V 11; [24] P 28, V 11. — ^{105}Ru: [6] V 11; [21] V 8, V 11. — >^{105}Ru: [6] S 31a, N 19b; [13] S 31a, N 19b; [14] S 31a. — ^{104}Rh: [6] C 51; [8] M 43; C 51; C 51; G 2; [16] D 32; [21] A 27, A 12, A 8, D 26, G 2, B 21, J 3, P 24, C 48, R 1, R 2, C 51, M 43. — ^{104}Rh*: [3, 4] P 24, C 48; [6] R 2; [7] P 24; [9] P 24; [16] D 32; [21] A 27, A 12, A 8, D 26, B 21, J 3, P 24, C 48, R 1, R 2, C 51, M 43. — ^{105}Rh: [6] V 11; [12] V 11; [18] L 33. — >^{105}Rh: [6] N 19b; [8] N 19b; [12] N 19b; [13] N 19b. — ^{107,109}Pd: [6] K 25; [8] K 25; [20] K 24, K 25; [21] A 27, M 16, K 25; [23] F 12; [24] K 25. — ^{111}Pd: [6] Y 3, S 31a; or $T = 17$ *m* after K 25; [13] Y 3, S 31a; [14] S 31a; [20] K 25, P 30; [21] A 27, K 25. — ^{112}Pd: [6] Y 3; [13] Y 3, N 19a, S 31a; [14] S 31a. — $^{(102)}$Ag: [6] E 5; [16] E 5. — $^{(104)}$Ag: [6] E 5; [16] E 5. — $^{(105)}$Ag: [6] E 5; [7] E 5; [9] E 5; [16] E 5. — ^{106}Ag: [6] E 5; [8] F 12; P 30; K 25; [9] F 12; [15] P 29, P 30, K 12; [16] D 28, E 5, W 14; [17] D 28; [18] K 24, K 25, P 30; [19] K 26, K 27, G 13a; [23] P 29, P 30; [24] P 26, P 28, H 51, C 13, R 27, P 29, K 25, P 30, R 5, F 12; [25] B 47, C 13, B 51, P 30, B 52, B 53. — ^{106}Ag*: [3, 4] P 29;

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	Fission of		(α, n)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	—	—	$^{102}_{44}$Ru	$^{102}_{44}$Ru	—	—	$^{101}_{44}$Ru	—	^{103}Ru
—	—	—	—	$^{104}_{45}$Rh	—	($^{105}_{45}$Rh)	—	—	$^{105}_{44}$Ru	—	—	$^{103}_{44}$Ru	—	^{104}Ru
$^{105}_{45}$Rh	—	—	—	—	—	—	—	—	$^{104}_{44}$Ru	—	—	—	—	^{105}Ru
>$^{105}_{45}$Rh	$^{238}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	>^{105}Ru
—	—	—	$^{106}_{47}$Ag	—	—	—	—	—	$^{104}_{45}$Rh	—	—	—	—	^{103}Rh
—	—	—	—	$^{104}_{44}$Ru	—	—	—	—	$^{103}_{45}$Rh	—	—	—	—	^{104}Rh
—	—	—	—	$^{105}_{44}$Ru	—	—	—	—	$^{104}_{45}$Rh	—	—	—	—	^{104}Rh*
$^{105}_{44}$Ru	—	—	—	—	—	($^{104}_{44}$Ru)	—	—	—	—	—	—	—	^{105}Rh
>$^{105}_{44}$Ru	$^{238}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{105}Rh
—	—	—	—	($^{102}_{47}$Ag)	—	—	—	—	—	—	—	—	—	^{102}Pd
—	—	—	—	($^{104}_{47}$Ag)	(p, γ)	—	—	—	—	—	—	—	—	^{104}Pd
—	—	—	—	($^{105}_{47}$Ag)	($^{106}_{47}$Ag)	$^{106}_{47}$Ag	—	—	—	—	—	—	—	^{105}Pd
—	—	—	—	$^{106}_{47}$Ag	—	—	—	$^{107}_{46}$Pd	$^{107}_{46}$Pd	—	—	—	—	^{106}Pd
$^{107}_{47}$Ag*	—	—	(α, p)	—	—	—	—	$^{108}_{46}$Pd	$^{108}_{46}$Pd	or	$^{107}_{47}$Ag	($^{108}_{46}$Pd)	—	^{107}Pd
or	—	—	$^{111}_{47}$Ag	$^{108}_{47}$Ag	—	—	or	$^{109}_{46}$Pd	$^{109}_{46}$Pd	or	—	($^{107}_{46}$Pd)	—	^{108}Pd
$^{109}_{47}$Ag*	—	—	—	—	—	—	—	$^{108}_{46}$Pd	$^{108}_{46}$Pd	—	$^{109}_{47}$Ag	($^{110}_{46}$Pd)	or	^{109}Pd
—	—	—	—	—	—	$^{111}_{47}$Ag	—	$^{111}_{46}$Pd	$^{111}_{46}$Pd	—	—	($^{109}_{46}$Pd)	—	^{110}Pd
$^{111}_{47}$Ag	$^{238}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	$^{110}_{46}$Pd	$^{110}_{46}$Pd	—	—	—	—	^{111}Pd
$^{112}_{47}$Ag	$^{238}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{112}Pd
—	—	—	—	($^{102}_{46}$Pd)	—	—	($d, {}^3_1$H)	—	—	—	—	—	—	(^{102})Ag
—	—	—	—	($^{104}_{46}$Pd)	—	—	—	—	—	—	—	—	—	(^{104})Ag
—	—	—	—	($^{105}_{46}$Pd)	—	—	—	—	—	—	—	—	—	(^{105})Ag
—	—	—	$^{103}_{45}$Rh	$^{106}_{46}$Pd	($^{105}_{46}$Pd)	$^{106}_{46}$Pd	$^{107}_{47}$Ag	—	—	—	$^{106}_{45}$Cd	$^{107}_{47}$Ag	$^{107}_{47}$Ag	^{106}Ag
—	(γ, —)	—	$^{103}_{45}$Rh	$^{108}_{46}$Pd	—	$^{105}_{46}$Pd	—	—	—	(n, n)	$^{108}_{46}$Cd	$^{107}_{47}$Ag	—	^{106}Ag*
—	$^{107}_{47}$Ag*	—	$^{110}_{49}$In	$^{107}_{46}$Cd^1	^{107}Cd$^{1,2}_{48}$	—	$^{106}_{47}$Ag	$^{108}_{47}$Ag	$^{108}_{47}$Ag	$^{107}_{47}$Ag*	$^{107}_{46}$Pd	$^{106}_{47}$Ag	$^{106}_{47}$Ag	^{107}Ag
$^{107}_{48}$Cd^{1,2}; $^{107}_{46}$Pd	$^{107}_{47}$Ag	—	—	—	—	—	—	—	—	$^{107}_{47}$Ag	—	—	—	^{107}Ag*
—	or	—	—	$^{108}_{46}$Pd	or	or	—	$^{107}_{47}$Ag	$^{107}_{47}$Ag	or	$^{108}_{46}$Cd	$^{108}_{47}$Ag	$^{108}_{47}$Ag	^{108}Ag
or or	—	($\alpha, 2n$)	—	—	—	—	—	$^{107}_{47}$Ag —	$^{107}_{47}$Ag	—	or	—	—	(^{108})Ag*
—	$^{109}_{47}$Ag*	$^{111}_{49}$In	$^{112}_{49}$In	$^{109}_{46}$Cd^1	^{109}Cd$^{1,2}_{48}$	—	—	—	$^{110}_{47}$Ag	$^{109}_{47}$Ag*	$^{109}_{46}$Pd	$^{108}_{47}$Ag	$^{108}_{47}$Ag	^{109}Ag
$^{109}_{48}$Cd^{1,2}; $^{109}_{46}$Pd	$^{109}_{47}$Ag	—	—	—	—	—	or	—	—	$^{109}_{47}$Ag	—	—	—	^{109}Ag*
—	—	—	—	—	—	—	—	—	$^{109}_{47}$Ag	—	$^{110}_{46}$Cd	—	—	^{110}Ag
—	—	—	(α, p)	—	—	—	—	$^{109}_{47}$Ag —	$^{109}_{47}$Ag	—	—	—	—	(^{110})Ag*
$^{111}_{46}$Pd	$^{238}_{92}$U	$^{232}_{90}$Th	$^{108}_{46}$Pd	—	—	$^{110}_{46}$Pd	—	—	—	—	$^{111}_{46}$Cd	—	—	^{111}Ag
$^{112}_{46}$Pd	$^{238}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	$^{111}_{48}$In	$^{112}_{46}$Cd	—	—	^{112}Ag
—	—	—	—	—	—	—	—	—	—	—	$^{106}_{47}$Ag	—	—	^{106}Cd
$^{107}_{47}$Ag*	—	—	—	$^{107}_{47}$Ag	$^{107}_{47}$Ag	—	—	—	—	—	—	—	—	^{107}Cd^1
$^{107}_{47}$Ag*	—	—	—	or	$^{107}_{47}$Ag	—	—	—	—	—	—	—	—	^{107}Cd^2
or	—	—	—	—	or	—	—	—	—	—	$^{108}_{47}$Ag	—	—	^{108}Cd
$^{109}_{47}$Ag*	—	—	—	$^{109}_{47}$Ag	$^{109}_{47}$Ag	—	—	—	—	—	—	—	—	^{109}Cd^1
$^{109}_{47}$Ag*	—	—	—	—	$^{109}_{47}$Ag	—	—	—	—	—	—	—	—	^{109}Cd^2
—	—	—	—	—	—	—	—	—	—	—	—	($^{110}_{48}$)Cd	—	(^{109})Cd
—	—	—	$^{113}_{50}$Sn	$^{110}_{49}$In	$^{110}_{49}$In	$^{111}_{49}$In	—	—	—	—	$^{110}_{47}$Ag	($^{109}_{48}$)Cd	—	^{110}Cd

[6] E 5; [7] P 30, F 12, R 9; [9] E 5; P 30, R 9; [15] P 29; [16] K 26; [18] K 24, K 25, P 30, [23] P 29, P 30; [24] P 29, K 25, P 30, F 12, R 9. — $^{107, 109}$Ag*: [3, 4] A 23; [6] A 23; [7] A 23; [9] A 23; V 3; [12] C 33, A 23, H 31a; S 31a; [13] F 13a; [22] B 23, G 21. — ^{108}Ag: [6] R 2; [8] G 10; N 4; [16] D 28, E 5; [20] K 26; [21] A 27, F 18, N 4, K 25, R 4, P 30, R 1, R 2, G 1; [23] P 30; [24] P 26, P 28, H 51, K 25, P 30; [25] B 47, C 13, B 51, P 30, B 52, B 53. — $^{(108, 110)}$Ag*: [3, 4] R 4; [6] L 41; [20] K 26; [21] M 39, R 4, A 7, L 41. — ^{110}Ag: [6] A 27, P 30; [8] G 2; [21] A 27, A 12, F 18, G 2, K 25, P 30, R 1, R 2; [23] P 30. — ^{111}Ag: [5] P 30; [8] K 25; Y 3; [9] K 25, P 30; [12] K 25, P 30; [13] Y 3, N 19a, S 31a; [14] S 31a; [15] P 30; [18] K 25, P 30; [23] P 30. — ^{112}Ag: [6] P 30; [8] P 30; Y 3; [12] Y 3, N 19a, S 31a; [13] Y 3, N 19a, S 31a; [14] S 31a; [22] P 30; [23] P 30. — $^{107, 109}$Cd^1: [6] D 18; [7] D 18, V 3, A 23; [9] V 3; [16] R 17, D 18, V 3, W 14; [17] K 26, A 23. — $^{107, 109}$Cd^2: [6] H 31a; [7] H 31a; [17] H 31a. — $^{(109)}$Cd: [6] P 28; [24] H 51, P 28.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
48	Cd	**63**	**111**	13.0	—	—	—	—	—	—
		64	**112**	24.2	—	—	—	—	—	—
		65	**113**	12.3	—	—	—	—	—	—
		66	**114**	28.0	—	—	—	—	—	—
		67	115	—	56 *h*	β^-	1.11; 0.6, 1.13 ± 0.03	0.8; 0.54	—	—
		(67)	(115)	—	40 *d*	—	0.95	—	—	—
		68	**116**	7.3	—	—	or —	—	—	—
		69	117	—	[170 ± 10] *m*	β^-	> 1.3	—	—	—
		(69)	(117)	—	—	—	—	—	—	—
	*	?	? *)	—	[50 ± 5] *m*	γ	—	—	—	—
49	**In**	61	110	—	[66 ± 5] *m*	β^+	2.0 ± 0.1; 1.6 ± 0.3	—	—	—
		62	111	—	[23.0 ± 1.0] *m*	β^+	1.75; 1.7	0.16 ± 0.01	—	—
		63	112	—	65 *h*	*K*	—	0.1728 ± 0.001, 0.2467 ± 0.001	—	—
		64	**113**	4.5	—	—	—	—	—	—
		isomer		—	[104 ± 2] *m*	γ	—	0.39 ± 0.02	—	—
		65	114	—	72 *s*	β^-	1.98 ± 0.03; 2.15	—	—	—
		isomer		—	[48.5 ± 2] *d*	γ	—	0.1917 ± 0.001	—	—
		66	**115**	95.5	—	—	—	—	—	—
		isomer		—	[272 ± 2] *m*	γ	—	0.3377 ± 0.001	—	—
		67	116	—	13 *s*	β^-	2.8; 3.2	none	—	—
		isomer		—	[56.8 ± 0.9] *m*	β^-	0.85 ± 0.01; 0.84 ± 0.01	0.17, 0.36, 0.57, 1.02, 1.40, 1.85 ± 0.03 ± 0.05		—
		68	117	—	[117 ± 3] *m*	β^-	1.73; 1.7	—	—	—
50	**Sn**	**62**	**112**	1.1	—	—	—	—	—	—
		63	113	—	[105 ± 15] *d*	*K*	—	0.085 ± 0.01	—	—
		64	**114**	0.8	—	—	—	—	—	—
		65	**115**	0.4	—	—	—	—	—	—
		66	**116**	15.5	—	—	—	—	115.943	4.8
		67	**117**	9.1	—	—	—	—	—	—
		68	**118**	22.5	—	—	—	—	117.940	3.8
		69	**119**	9.8	—	—	—	—	118.938	3.8
		70	**120**	28.5	—	—	—	—	—	—
		(71)	(121)	—	26 *h*	β^-	—	—	—	—
		72	**122**	5.5	—	—	—	—	121.946	5.0
		(73)	(123)	—	40 *m*	β^-	—	—	—	—
		74	**124**	6.8	—	—	—	—	123.945	5.1
		75	125	—	[11.8 ± 0.5] *m*	β^-	2.1	—	—	—
	1	< 76	< 126	—	10 *d*	β^-	—	—	—	—
	2	< 76	< 126	—	~400 *d*	β^-	—	—	—	—
51	**Sb**	67	118	—	3.6 *m*	β^+	—	—	—	—
		69	120	—	[15 ± 0.8] *m*	β^+	1.53	—	—	—
		70	**121**	56	—	—	—	—	—	—
		71	122	—	63 *h*	β^-	0.81, 1.76 ± 0.10; 1.64	0.96; 0.5	—	—

^{115}Cd: [6] C 33; [8] C 33; L 22; [9] C 33; L 22; [13] Y 3, N 19a; [20] C 31, L 20, L 21, C 33, L 22; [21] M 37, G 13; [24] G 13. — $^{(115, 117)}$Cd: [6] C 33; [8] C 33; [20] C 33. — ^{117}Cd: [6] L 22; [8] L 22; [13] Y 3, N 19a; [20] C 31, L 20, C 33; [21] H 51, M 37, G 13. — ^{7}Cd*: [3, 4] *) isomer of a stable Cd nucleus: D 22, F 13a; [6] D 22; or $T = 1\ h$ after F 13a; [7] D 22; [13] Y 3, N 19a; [22] D 22; [25] F 13a. — ^{110}In: [6] B 13; [8] L 22; B 13; [15] K 5, L 22; [16] B 13; [17] L 22. — ^{111}In: [6] L 22; [8] L 20; L 22; [9] B 13; [14] K 12, K 13, L 22; [16] B 13; [18] L 20, C 33, L 22. — ^{112}In: [6] C 33, L 22; [7] L 22; [9] L 22; [15] L 22; [16] B 13; [18] C 33, L 22; [24] C 33, L 22. — ^{113}In*: [3, 4] B 13; [6] L 22; [7] B 13, L 22; [9] B 13; [12] B 13; [16] B 13; [18] L 22. — ^{114}In: [6] L 20; [8] L 22; L 20; [16] B 13; [18] L 20; [24] C 13, P 28, L 20, L 22; [25] B 48, C 13, B 51. — ^{114}In*: [3, 4] L 22; [6] B 13; [7] B 13, L 22; [9] L 22; [16] B 12, B 13, W 14; [18] L 20, C 33, L 22; [20] L 20, L 22; [21] M 39, A 7; [24] L 20. — ^{115}In*: [3, 4] G 13; [6] L 22; [7] L 21, L 22; [9] L 22; [12] G 13, C 33, Y 3; [13] Y 3, N 19a; [14] L 8, R 19; [17] B 12, B 13; [18]

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	Fission of		(α, n)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	$^{111}_{49}$In	—	$^{112}_{49}$In	—	—	—	—	$^{111}_{47}$Ag	—	—	^{111}Cd
—	—	—	—	$^{112}_{49}$In	—	$^{113}_{49}$In*	—	—	—	—	$^{112}_{47}$Ag	—	—	^{112}Cd
—	—	—	—	$^{113}_{49}$In*	—	$^{114}_{49}$In*	—	—	—	—	—	—	—	^{113}Cd
—	—	—	—	$^{114}_{49}$In	—	$^{115}_{49}$In*	—	$^{115}_{48}$Cd	$^{115}_{48}$Cd	—	—	—	—	^{114}Cd
$^{115}_{49}$In*	$^{238}_{92}$U	—	—	—	—	—	—	$^{115}_{48}$Cd	$^{116}_{48}$Cd	—	—	$^{116}_{48}$Cd	—	^{115}Cd
—	—	—	—	—	—	—	—	$(^{114})_{48}$Cd	—	—	—	—	—	$(^{113})$Cd
—	—	—	—	$^{116}_{49}$In	—	$^{117}_{49}$In	or	$^{117}_{48}$Cd	$^{117}_{48}$Cd	—	—	$^{115}_{48}$Cd	—	^{116}Cd
$^{117}_{49}$In	$^{238}_{92}$U	—	—	—	—	—		$^{118}_{48}$Cd	$^{118}_{48}$Cd		—	—		^{117}Cd
—	—	—	—	—	—	—		$(^{119})_{48}$Cd	—	(n, n)	—	—	$(\gamma, —)$	$(^{117})$Cd
—	$^{238}_{92}$U	—	—	—	—	—	—	—	—	$^{?}_{48}$Cd	—	—	$^{?}_{48}$Cd	$^{?}$Cd*
—	—	$(\alpha, 2n)$	$^{107}_{47}$Ag	$^{110}_{48}$Cd	$^{110}_{48}$Cd	—	—	—	—	—	—	—	—	^{110}In
—	—	$^{108}_{47}$Ag	—	$^{111}_{48}$Cd	—	$^{110}_{48}$Cd	—	—	—	—	—	—	—	^{111}In
—	—	—	$^{109}_{47}$Ag	$^{112}_{48}$Cd	—	$^{111}_{48}$Cd	—	—	—	—	—	$^{112}_{49}$In	—	^{112}In
—	—	—	—	$^{112}_{50}$Sn	—	—	—	$(^{114}_{49}$In*)	$^{114}_{49}$In*	—	—	$^{113}_{49}$In	—	^{113}In
$^{113}_{50}$Sn	—	—	—	$^{113}_{48}$Cd	—	$^{112}_{48}$Cd	—	—	—	—	—	—	—	^{113}In*
—	—	—	—	$^{114}_{48}$Cd	—	$(^{113}_{48}$Cd)	—	—	—	—	—	$^{115}_{49}$In	$^{115}_{49}$In	^{114}In
—	—	(α, α)	—	$^{114}_{48}$Cd	(p, p)	$^{113}_{48}$Cd	$(\gamma, —)$	$(^{113}_{49}$In)	$^{113}_{49}$In	—	(n, n)	$^{115}_{49}$In	—	^{114}In*
—	—	$^{115}_{49}$In*	$^{118}_{51}$Sb	—	$^{115}_{49}$In*	—	$^{115}_{49}$In*	$^{116}_{49}$In	$^{116}_{49}$In	$^{113}_{47}$Ag	$^{115}_{49}$In*	$^{114}_{49}$In	$^{114}_{49}$In	^{115}In
$^{115}_{48}$Cd	$^{238}_{92}$U	$^{115}_{49}$In	—	—	$^{115}_{49}$In	$^{114}_{48}$Cd	$^{115}_{49}$In *)	—	—	—	$^{115}_{49}$In *)	—	—	^{115}In*
—	—	—	—	$^{116}_{48}$Cd	—	—	—	$(^{115}_{49}$In)	$^{115}_{49}$In	—	—	—	—	^{116}In
—	—	—	—	$^{116}_{48}$Cd	—	—	—	$^{116}_{49}$In	$^{115}_{49}$In	—	—	—	—	^{116}In*
$^{117}_{48}$Cd	$^{238}_{92}$U	—	—	—	—	$^{116}_{48}$Cd	—	—	—	—	—	—	—	^{117}In
—	—	—	—	—	—	—	—	$^{112}_{50}$Sn	$^{112}_{50}$Sn	—	—	—	—	^{112}Sn
$^{113}_{49}$In*	—	—	$^{110}_{48}$Cd	$^{113}_{49}$In	—	—	—	$^{113}_{50}$Sn	$^{113}_{50}$Sn	—	—	—	—	^{113}Sn
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{114}Sn
—	—	—		—	—	—	—	—	—	—	—	—	—	^{115}Sn
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{116}Sn
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{117}Sn
—	—	—	$^{121}_{52}$Te	$(^{118}_{51}$Sb)	—	—	—	—	—	—	—	—	—	^{118}Sn
—	—	—	—	—	—	$^{120}_{51}$Sb	—	—	—	—	—	—	—	^{119}Sn
—	—	—	—	$^{120}_{51}$Sb	—	—	—	$(^{121})_{50}$Sn	$(^{121})_{50}$Sn	—	—	—	—	^{120}Sn
—	—	—	—	—	—	—	$(^{122}_{51}$Sb)	$(^{120})_{50}$Sn	$(^{120})_{50}$Sn	—	—	—	—	$(^{121})$Sn
—	—	—	—	$^{122}_{51}$Sb	$^{122}_{51}$Sb	—	—	$(^{122})_{50}$Sn	$(^{122})_{50}$Sn	—	—	—	—	^{122}Sn
—	—	—	—	—	—	—	—	$(^{123})_{50}$Sn	$(^{123})_{50}$Sn	—	—	$(^{124})_{50}$Sn	—	$(^{123})$Sn
—	—	—	—	—	—	—	—	$^{125}_{50}$Sn	$^{125}_{50}$Sn	—	—	$(^{123})_{50}$Sn	—	^{124}Sn
—	—	—	—	—	—	—	—	$^{125}_{50}$Sn	$^{125}_{50}$Sn	—	—	—	—	^{125}Sn
—	—	—	—	—	—	—	—	$^{?}_{50}$Sn	$^{?}_{50}$Sn	—	—	—	—	$<^{126}$Sn^{1}
—	—	—	—	—	—	—	—	$^{?}_{50}$Sn	—	—	—	—	—	$<^{126}$Sn^{2}
—	—	—	$^{115}_{49}$In	—	—	—	—	—	—	—	—	—	—	^{118}Sb
—	—	—	—	$^{120}_{50}$Sn	—	$^{119}_{50}$Sn	—	—	—	—	—	$^{121}_{51}$Sb	$^{121}_{51}$Sb	^{120}Sb
—	—	—	$^{124}_{53}$I	$^{121}_{52}$Te	$^{121}_{52}$Te	—	—	$^{122}_{51}$Sb	$^{122}_{51}$Sb	—	—	$^{120}_{51}$Sb	$^{120}_{51}$Sb	^{121}Sb
—	—	—	—	$^{122}_{50}$Sn	$^{122}_{50}$Sn	—	—	$^{121}_{51}$Sb	$^{121}_{51}$Sb	—	—	—	—	^{122}Sb

L 20, L 21, C 33, L 22; [19] P 25, C 25, C 27, K 22, N 22; *) also $^{115}_{49}$In (e^-, e^-) $^{115}_{49}$In*: C 27; [23] S 61, L 20, G 13; *) also ($^{115}_{49}$In ($\bar{d}$, $\bar{d}$) $^{115}_{49}$In*): L 20. — ^{116}In: [6] A 27; [8] C 33; G 2; [9] M 40; [16] D 32; [20] L 20; [21] A 27, G 2, P 28, L 20, M 40. — ^{116}In*: [3, 4] L 20; [6] Z 1; [8] C 33; C 63; [9] C 63; [16] B 13; [20] L 20; [21] A 27, S 61, G 2, B 59, M 38, P 28, L 20, M 39, M 40, G 22, Z 1, C 63. — ^{117}In: [6] L 22; [8] C 33; L 22; Y 3; [12] G 13, C 33, Y 3, L 22; [13] Y 3, N 19a; [18] C 31, L 20, C 33, L 22. — ^{112}Sn: [6] B 13; [7] B 13; [9] B 13; [15] L 47; [16] B 13; [20] L 34, L 47; [21] L 47. — $^{(121)}$Sn: [6] L 47; [19] L 33, L 47; [20] L 34, L 47; [21] L 47. — $^{(123)}$Sn: [6] L 47; [20] L 34, L 47; [21] L 47; [24] P 28. — ^{125}Sn: [6] Z 1; [8] Z 1; [20] L 34, L 47; [21] N 3, N 1, N 2, L 47, Z 1. — $<^{126}$Sn^{1}: [6] L 47; [20] L 47; [21] L 47. — $<^{126}$Sn^{2}: [6] L 47; [20] L 47. — ^{118}Sb: [6] R 19; [15] L 8, R 19. — ^{120}Sb: [6] B 51; [8] A 25; [16] D 32; [18] L 36, L 45; [24] H 51, C 13, L 36, P 28, A 25; [25] B 47, C 13, B 51, B 53. — ^{122}Sb: [6] M 42; [8] M 42; A 25; [9] M 42; L 49; [16] D 32; [17] L 45; [20] L 33, L 36; [21] A 27, L 36, A 25, M 41, M 42.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
51	Sb	**72**	**123**	44	—	—	—	—	—	—
		73	124	—	60 *d*	β^-, *K*	1.53 ± 0.05; 1.8	< 0.069, 1.82 ± 0.05; 0.8		—
	1	<75	<126	—	3 *h*	β^-	—	—	—	—
	2	<75	<126	—	~45 *d*	—	—	—	—	—
	3	<75	<126	—	~2 *a*	—	—	—	—	—
		76	127	—	80 *h*	β^-	—	—	—	—
		78	129	—	4.2 *h*	β^-	—	—	—	—
		(82)	(133)	—	(10 *m*)	β^-	—	—	—	—
		>80	>131	—	5 *m*	β^-	—	—	—	—
52	Te	**68**	**120**	rare	—	—	—	—	—	—
		69	121	—	[125 ± 5] *d*	(*K*, β^+)	—	(0.5)	—	—
		70	**122**	2.9	—	—	—	—	—	—
		71	**123**	1.6	—	—	—	—	—	—
		72	**124**	4.5	—	—	—	—	—	—
		73	**125**	6.0	—	—	—	—	—	—
		74	**126**	19.0	—	—	—	—	—	—
		75	127	—	[9.3 ± 0.5] *h*	β^-	0.8	—	—	—
		isomer		—	[90 ± 2] *d*	γ	—	0.125	—	—
		76	**128**	32.8	—	—	—	—	—	—
		77	129	—	[72 ± 3] *m*	β^-	—	—	—	—
		isomer		—	[32 ± 2] *d*	γ	—	0.1	—	—
		78	**130**	33.1	—	—	—	—	—	—
		79	131	—	[25 ± 5] *m*	β^-	—	—	—	—
		isomer		—	[1.2 ± 0.2] *d*	γ	—	0.165	—	—
		81	133	—	60 *m*	β^-	—	—	—	—
		83	135	—	~15 *m*	β^-	—	—	—	—
	1	>79	>131	—	77 *h*	β^-	—	—	—	—
	2	>79	>131	—	43 *m*	β^-	—	—	—	—
53	I	71	124	—	[4.0 ± 0.3] *d*	β^+	—	—	—	—
		73	126	—	[13.3 ± 0.3] *d*	β^-	1.20 ± 0.03; 1.13	0.5	—	—
		74	**127**	100	—	—	—	—	—	—
		75	128	—	[25 ± 1] *m*	β^-	1.05, 2.10 ± 0.05; 2.40 ± 0.07; 2.1; 2.2; *1.2, 2.1*	0.4; 0.4—0.5	—	—
		77	130	—	[12.5 ± 0.5] *h*	β^-	0.83 ± 0.03; 1.05	0.59; 0.6	—	—
		78	131	—	[8.0 ± 0.2] *d*	β^-	0.687 ± 0.010; 0.595 ± 0.015; 1.24	0.27, 0.46; 0.364 ± 0.02	—	—
		80	133	—	18.5 *h*	β^-	—	—	—	—
		82	135	—	[6.6 ± 0.3] *h*	β^-	—	—	—	—
	1	>78	>131	—	2.4 *h*	β^-	—	—	—	—
	2	>78	>131	—	54 *m*	β^-	—	—	—	—
	3	>78	>131	—	[1.8 ± 0.4] *m*	β^-	—	—	—	—
	4	>78	>131	—	[30 ± 6] *s*	β^-	—	—	—	—

^{124}Sb: [6] L 45; [7] M 42; [8] M 42; L 49; [9] M 42; L 49; [19] T 1; [20] L 33, L 36; [21] L 36, A 6, M 41, M 42; [22] L 45. — <^{126}Sb^1: [6] L 45; [18] L 45. — <^{126}Sb^2: [6] L 45; [18] L 45. — <^{126}Sb^3: [6] L 45; [18] L 45. — ^{127}Sb: [6] A 5; [13] A 4, A 5, A 31a. — ^{129}Sb: [6] A 5; [13] A 3, A 4, A 5, A 31a. — $^{(133)}$Sb: [6] S 33; [13] S 33; [14] S 33. — >^{131}Sb: [6] A 5; [13] A 3, A 5. — ^{121}Te: [6] S 27; [7] S 27; [9] S 27; [15] S 27; [16] S 25, S 27; [17] S 25, S 27. — ^{127}Te: [6] S 27; [8] S 27; [12] S 25, S 27; A 4, A 5; A 31a; [13] A 4, A 5, A 31a; [20] T 1, S 25, A 5, S 27; [21] S 27; [23] L 39, S 25, S 27; [24] T 1. — ^{127}Te*: [3, 4] S 25, S 27; [6] S 27; [7] S 25, S 27; [9] S 27; [20] S 25, A 5, S 27; [21] S 27; [23] S 25, S 27. — ^{129}Te: [6] S 27; [12] S 25, S 27; A 3, A 4, A 5, A 31a; [13] A 3, A 4, A 5, A 31a; [20] T 1, L 44, S 25, A 5, S 27; [21] A 27, L 44, S 27, Z 1; [24] H 51, P 28, T 1; [25] B 48, B 51, B 53. — ^{129}Te*: [3, 4] S 25, S 27; [6] S 27; [7] S 25, S 27; [9] S 27; [20] T 1, S 25, A 5, S 27; [24] P 28, T 1. — ^{131}Te: [6] S 27; [12] S 24, S 25, S 27; [13] A 4, A 5; [20] L 44, S 24, S 25, S 27, D 18d; [21] A 27, L 44, S 24, S 25, S 27, Z 1. — ^{131}Te*: [3, 4] S 24, S 25, S 27; [6] S 27; [7] S 24, S 25, S 27; [9] S 27; [13] A 4, A 5; [20] L 44, S 24, S 25, S 27; [21] L 44, S 24, S 25, S 27. — ^{133}Te: [6] A 5; [12] S 33; [13] A 3, A 4, A 5, S 33; [14] S 33. — ^{135}Te: [6] S 33; [13] S 33; [14] S 33. —

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	Fission of		(α, n)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	$^{126}_{53}$I	—	—	—	($^{121}_{50}$Sn)	$^{124}_{51}$Sb	$^{124}_{51}$Sb	—	—	—	—	^{123}Sb
—	—	—	—	—	—	—	$^{120}_{52}$Te	$^{123}_{51}$Sb	$^{123}_{51}$Sb	$^{127}_{53}$I	—	—	—	^{124}Sb
—	—	—	—	—	—	?Sn	—	—	—	—	—	—	—	<^{126}Sb[1]
—	—	—	—	—	—	?Sn	—	—	—	—	—	—	—	<^{126}Sb[2]
—	—	—	—	—	—	?Sn	—	—	—	—	—	—	—	<^{126}Sb[3]
$^{127}_{52}$Te	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	^{127}Sb
$^{129}_{52}$Te	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	^{129}Sb
($^{132}_{52}$Te)	($^{235}_{92}$U)	($^{232}_{90}$Th)	—	—	—	—	—	—	—	—	—	—	—	(^{133})Sb
> $^{131}_{52}$Te[1]	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{131}Sb
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{120}Te
—	—	—	$^{118}_{50}$Sn	$^{121}_{51}$Sb	$^{121}_{51}$Sb	—	—	—	—	—	—	—	—	^{121}Te
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{122}Te
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{123}Te
—	—	—	—	$^{124}_{53}$I	—	—	—	—	—	—	—	—	—	^{124}Te
—	—	—	—	—	—	$^{126}_{53}$I	—	—	—	—	—	—	—	^{125}Te
—	—	—	—	$^{126}_{53}$I	—	—	$^{124}_{51}$Sb	$^{127}_{52}$Te	$^{127}_{52}$Te	—	—	—	—	^{126}Te
$^{127}_{52}$Te*; $^{127}_{51}$Sb	$^{235}_{92}$U	—	—	—	—	—	—	$^{126}_{52}$Te	$^{126}_{52}$Te	—	$^{127}_{53}$I	$^{132}_{52}$Te	—	^{127}Te
$^{127}_{52}$Te	—	—	—	—	—	—	—	$^{126}_{52}$Te	$^{126}_{52}$Te	—	$^{127}_{53}$I	—	—	^{127}Te*
—	—	—	—	$^{128}_{53}$I	$^{128}_{53}$I	—	—	$^{129}_{52}$Te	$^{129}_{52}$Te	—	—	$^{127}_{51}$Te	—	^{128}Te
$^{129}_{52}$Te*; $^{129}_{51}$Sb	$^{235}_{92}$U	—	—	—	—	—	—	$^{128}_{52}$Te	$^{128}_{52}$Te	—	—	$^{130}_{52}$Te	$^{130}_{52}$Te	^{129}Te
$^{129}_{52}$Te	—	—	—	—	—	—	—	$^{128}_{52}$Te	—	—	—	$^{130}_{52}$Te	—	^{129}Te*
—	—	—	$^{133}_{54}$X	$^{130}_{53}$I	$^{130}_{53}$I	$^{131}_{53}$I	—	$^{131}_{52}$Te	$^{131}_{52}$Te	—	—	$^{129}_{52}$Te	$^{129}_{52}$Te	^{130}Te
$^{131}_{52}$Te* $^{131}_{53}$I	$^{235}_{92}$U	—	—	—	—	—	—	$^{130}_{52}$Te	$^{130}_{52}$Te	—	—	—	—	^{131}Te
$^{131}_{52}$Te	$^{235}_{92}$U	—	—	—	—	—	—	$^{130}_{52}$Te	$^{130}_{52}$Te	—	—	—	—	^{131}Te*
($^{133}_{51}$Sb) $^{133}_{53}$I	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{133}Te
$^{135}_{53}$I	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{135}Te
>$^{131}_{51}$Sb > $^{131}_{53}$I[1]	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	>^{131}Te[1]
> $^{131}_{53}$I[2]	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	>^{131}Te[2]
—	—	—	$^{121}_{51}$Sb	$^{124}_{52}$Te	—	—	(p, γ)	—	—	—	—	—	—	^{124}|
—	—	—	$^{123}_{51}$Sb	$^{126}_{52}$Te	—	$^{125}_{52}$Te	—	—	—	—	—	$^{127}_{53}$I	—	^{126}|
—	—	—	—	$^{127}_{54}$X	—	or	—	$^{128}_{54}$X	—	$^{128}_{53}$I	$^{124}_{51}$Sb	$^{127}_{52}$Te	$^{126}_{53}$I	^{127}|
—	—	—	—	$^{128}_{52}$Te	$^{128}_{52}$Te	—	—	—	—	$^{127}_{53}$I	—	—	—	^{128}|
—	—	—	—	$^{130}_{52}$Te	$^{130}_{52}$Te	—	—	—	—	$^{133}_{55}$Cs	—	—	—	^{130}|
$^{131}_{52}$Te	$^{235}_{92}$U	—	—	—	—	$^{130}_{52}$Te	—	—	—	—	—	—	—	^{131}|
$^{133}_{52}$Te $^{133}_{54}$X	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{133}|
$^{135}_{52}$Te $^{135}_{54}$X; $^{135}_{54}$X*	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{135}|
> $^{131}_{52}$Te[1]	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	>^{131}|[1]
> $^{131}_{52}$Te[2]	$^{235}_{92}$U	$^{232}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	>^{131}|[2]
—	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{131}|[3]
—	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	>^{131}|[4]

>^{131}Te[1]: [6] A 5; [12] A 3, A 5; [13] A 1, F 13, A 3, A 5, H 10, H 11, H 13, H 14; [14] H 12, H 13, P 11. — >^{131}Te[2]: [6] A 5; [13] A 3, A 4, A 5; [14] P 11. — ^{124}I: [6] L 44; [15] L 44; [16] D 32. — ^{124}I: [6] L 44; [8] T 3; L 44; [9] L 44; [15] L 44; [16] D 32; [18] L 39, L 44, T 3; [24] T 1, L 39, L 44, T 2. — ^{126}I: [6] L 44; [8] B 2a; T 3; A 8; L 44; B 2; [9] L 44; B 3; [16] D 32; [17] L 44, T 2, T 3; [21] A 27, A 12, E 7, E 8, A 8, F 6, P 28, T 1, B 2, B 3, C 49, B 2a. — ^{130}I: [6] T 3; [8] T 3; L 44; [9] T 3; L 44; [16] D 32; [17] L 39, L 44, T 3; [22] W 21. — ^{131}I: [6] L 44; [8] T 3; D 18d; L 44; [9] T 3; D 18d; [12] L 25, L 44, S 24, S 25, A 4, A 5, H 11, H 13, H 14, A 31a, D 18d; [13] A 4, A 5, H 11, H 13, H 14, A 31a; [18] T 1, L 39, L 44, T 2, A 5, T 3. — ^{133}I: [6] H 11; [12] A 3, A 5, H 11, H 13, H 14, S 33; [13] A 3, A 5, H 11, H 12, H 13, S 33, A 31a; [14] S 33, P 11. — ^{135}I: [6] D 24; [12] S 33; [13] S 33, G 12, D 24, A 31a; [14] S 33. — >^{131}I[1]: [6] A 5; [12] A 1, A 3, A 5, H 10, H 11, H 12, H 13, H 14, P 11; [13] A 1, F 13, A 3, A 5, H 10, H 11, H 13, H 14, A 31a; [14] H 12, H 13, P 11. — >^{131}I[2]: [6] A 3; [12] A 3, A 4, A 5, H 11, H 13, H 14, P 11; [13] A 3, A 4, A 5, H 11, H 13, H 14; [14] P 11. — >^{131}I[3]: [6] H 19a; [13] H 19a. — >^{131}I[4]: [6] H 19a; [13] H 19a.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Table IV

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
54	**X**	**70**	**124**	0.094	—	—	—	—	—	—
	(Xe)	**72**	**126**	0.088	—	—	—	—	—	—
		(73)	(127)	—	[34 ± 2] *d*	β^-	—	—	—	—
		74	**128**	1.91	—	—	or —	—	—	—
		(74)	(128)	—	[75 ± 1] *s*	(γ)	—	0.125, 0.175	—	—
		75	**129**	26.23	—	—	—	—	128.946	1.4
		76	**130**	4.06	—	—	—	—	—	—
		77	**131**	21.18	—	—	—	—	—	—
		78	**132**	26.98	—	—	—	—	132.946	~5
		79	133	—	[4.3 ± 0.4] *d*	γ	—	0.083	—	—
		80	**134**	10.55	—	—	—	—	—	—
		81	135	—	10 *m*	—	—	—	—	—
		isomer		—	[9.5 ± 0.4] *h*	—	—	—	—	—
		82	**136**	8.95	—	—	—	—	—	—
		(83)	(137)	—	68 *m*	—	—	—	—	—
		>82	>136	—	[17 ± 1] *m*	β^-	—	—	—	—
		85	139	—	45 *s*	β^-	—	—	—	—
		(86)	(140)	—	very short	β^-	—	—	—	—
55	**Cs**	**78**	**133**	100	—	—	—	—	—	—
		79	134	—	3 *h* ± 10 *m*	β^-	~1	none	—	—
		(isomer)		—	[20 ± 1] *mo*	β^-	0.9	intense	—	—
		>81	>136	—	[32 ± 0.5] *m*	β^-	2.6	—	—	—
		84	139	—	7 *m*	β^-	—	—	—	—
		(85)	(140)	—	40 *s*	β^-	—	—	—	—
56	**Ba**	**74**	**130**	0.101	—	—	—	—	—	—
		76	**132**	0.097	—	—	—	—	—	—
		77	133	—	[30 ± 1] *h*	—	—	0.25	—	—
	1	(77)	(133)	—	2.5 *m*	—	—	—	—	—
	2	(77)	(133)	—	340 *h*	—	—	0.017	—	—
		78	**134**	2.42	—	—	—	—	—	—
		(isomer)		—	39.5 *h*	(γ)	—	0.272	—	—
		79	**135**	6.6	—	—	—	—	—	—
		80	**136**	7.8	—	—	—	—	—	—
		81	**137**	11.3	—	—	—	—	—	—
		82	**138**	71.7	—	—	—	—	—	—
		83	139	—	[87 ± 1] *m*	β^-	~1	~0.6	—	—
		84	140	—	~300 *h*	β^-	—	—	—	—
		>84	>140	—	[14 ± 2] *m*	β^-	—	—	—	—
57	**La**	(81)	(138)	—	31 *h*	β^-	0.8	—	—	—
		82	**139**	100	—	—	—	—	—	—
		83	140	—	[44 ± 2] *h*	β^-	—	—	—	—
		>84	>140	—	2,5 *h*	β^-	—	—	—	—

$^{(127)}$X: [6] C 49; [16] B 8, C 49. — $^{(128)}$X: [6] C 49; [7] C 49; [9] C 49; [19] B 8, C 49. — ^{133}X: [6] D 24; [7] S 31b; [9] H 31a; [12] S 33; [13] S 33, D 24; [14] S 33; [15] C 16a; [20] C 16a; [22] W 21; [23] W 21. — ^{135}X: [6] G 12; [12] G 12; [13] G 12. — ^{135}X*: [3, 4] G 12; [6] D 24; [12] S 33, G 12, D 24; [13] S 33, G 12, D 24; [14] S 33; [20] C 16a; [22] W 21. — $^{(137)}$X: [6] C 16a; [20] C 16a. — >^{136}X: [6] G 10; [13] H 52, H 11, H 13, H 14, H 15, G 10; [14] A 33, H 16. — ^{139}X: [6] S 9; [13] H 9, H 52, H 11, H 13, H 14, H 15; [14] A 33, H 16. — $^{(140)}$X: [6] H 15; [13] H 15, G 10; [14] H 16. — ^{134}Cs: [6] K 2; [8] K 2; [9] K 2; [20] K 2; [21] A 27, M 17, L 11, K 2. — $^{(134)}$Cs*: [6] K 2; [8] K 2; [9] K 2; [20] K 2; [21] R 23, A 7, S 22, K 2. — >^{136}Cs: [6] G 10; [8] G 10; [12] H 9, H 52, A 32, H 11, H 15, H 16, S 28, G 10, H 19; [13] H 9, H 52, H 11, H 13, H 14, G 19, H 15, S 28, G 10, H 19; [13/14] G 19; [14] A 23, G 19, H 16. — ^{139}Cs: [6] H 15; [12] H 9, H 52, H 11, H 15, H 16, H 19; [13] H 9, H 52, H 11, H 13, H 14, H 15, H 19; [14] A 33, H 16. —

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	Fission of		(α, n)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	—	(p, γ)	—	—	—	—	—	—	^{124}X
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{126}X
—	—	—	—	$^{127}_{53}I$	—	—	—	—	—	—	—	—	—	$^{(127)}X$
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{128}X
—	—	—	—	—	or		$^{127}_{53}I$	—	—	—	—	—	—	$^{(128)}X$
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{129}X
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{130}X
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{131}X
—	—	—	—	—	—	—	—	$^{132}_{54}X$	—	—	—	—	—	^{132}X
$^{133}_{53}I$	$^{235}_{92}U$	$^{232}_{90}Th$	$^{130}_{52}Te$	—	—	—	—	$^{133}_{54}X$	—	$^{135}_{56}Ba$	$^{132}_{55}Cs$	—	—	^{133}X
—	—	—	—	—	—	—	—	$^{135}_{54}X^*$	—	—	—	—	—	^{134}X
$^{135}_{53}I$	$^{235}_{92}U$	—	—	—	—	—	—	—	—	—	—	—	—	^{135}X
$^{135}_{53}I$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	$^{134}_{54}X$	—	$^{138}_{56}Ba$	—	—	—	$^{135}X^*$
—	—	—	—	—	—	—	—	$^{(137)}_{54}X$	—	—	—	—	—	^{136}X
—	—	—	—	—	—	—	—	$^{(138)}_{54}X$	—	—	—	—	—	$^{(137)}X$
$>^{136}_{55}Cs$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	$>^{136}X$
$^{138}_{55}Cs$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	^{138}X
$^{(140)}_{55}Cs$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	$^{(140)}X$
—	—	—	—	$^{132}_{56}Ba$	$(^{(132)}_{56}Ba^2)$	$(^{(134)}_{56}Ba^*)$	—	$^{134}_{55}Cs$	$^{134}_{55}Cs$	$^{130}_{53}I$	$^{132}_{54}X$	—	—	^{133}Cs
—	—	—	—	—	—	—	—	$^{136}_{55}Cs$	$^{136}_{55}Cs$	—	—	—	—	^{134}Cs
—	—	—	—	—	—	—	—	$^{138}_{55}Cs$	$^{138}_{55}Cs$	—	—	—	—	$^{(134)}Cs^*$
$>^{136}_{54}X$	$^{235}_{92}U$, $^{231}_{91}Pa$,	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	$>^{136}Cs$
$^{139}_{54}X$ $^{139}_{56}Ba$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	^{139}Cs
$^{(140)}_{54}X$ $(^{140}_{56}Ba)$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	$^{(140)}Cs$
—	—	—	—	—	—	—	$(d, {}^2_1H)$	—	—	—	—	—	—	^{130}Ba
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{132}Ba
—	—	—	—	$^{132}_{55}Cs$	—	—	—	—	—	—	—	$^{134}_{56}Ba$	—	^{133}Ba
—	—	—	—	—	—	—	—	—	—	—	—	$^{134}_{56}Ba$	—	$^{(133)}Ba^1$
—	—	—	—	—	$(^{132}_{55}Cs)$	—	—	—	—	—	—	—	—	$^{(133)}Ba^2$
—	—	—	—	—	—	—	—	—	—	—	—	$^{133}_{56}Ba$	—	^{134}Ba
—	—	—	—	—	—	$(^{132}_{55}Cs)$	—	—	—	—	—	—	—	$^{(134)}Ba^*$
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{135}Ba
—	—	—	—	—	—	—	—	—	—	$^{133}_{54}X$	—	—	—	^{136}Ba
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{137}Ba
—	—	—	—	—	—	—	—	$^{138}_{56}Ba$	$^{138}_{56}Ba$	$^{135}_{54}X^*$	—	—	—	^{138}Ba
$^{139}_{55}Cs$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	$^{138}_{56}Ba$	$^{138}_{56}Ba$	—	$^{139}_{57}La$	—	—	^{139}Ba
$(^{140}_{55}Cs)$ $^{140}_{57}La$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	^{140}Ba
$>^{140}_{57}La$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	$>^{140}Ba$
—	—	—	—	—	—	—	$(^{139}_{57}La)$	—	—	—	—	$(^{139}_{57}La)$	—	$^{(138)}La$
—	—	—	—	—	—	—	$(^{138}_{57}La)$	—	$^{140}_{57}La$	—	$^{139}_{56}Ba$	$(^{138}_{57}La)$	—	^{139}La
$^{140}_{56}Ba$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	$^{139}_{57}La$	—	—	—	—	^{140}La
$>^{140}_{56}Ba$	$^{235}_{92}U$	$^{232}_{90}Th$	—	—	—	—	—	—	—	—	—	—	—	$>^{140}La$

$^{(140)}$Cs: [6] H 15; [12] H 15, G 10; [13] H 15, G 10; [14] H 16. — ^{132}Ba: [6] K 2; [9] K 2; [16] D 32; [24] K 1, K 2. — $^{(133)}$Ba^1: [6] P 28; [24] F 14, P 28, K 2. — $^{(133)}$Ba^2: [6] C 24a; [9] C 24a; [17] C 24a. — $^{(134)}$Ba*: [6] C 24a; [7] C 24a; [9] C 24a; [18] C 24a. — ^{139}Ba: [6] K 2; [8] K 2; [9] K 2; [12] H 9, H 52, H 11, H 15, H 16, H 19; [13] H 7, H 8, H 9, H 52, H 13, H 14, H 19; [14] A 33, H 12, H 13, H 16; [20] P 27, K 2; [21] A 27, A 28, H 52, P 28; [23] P 31. — ^{140}Ba: [6] H 7, H 9; [12] H 52, H 11, H 15, H 16, G 10; [13] H 7, H 8, H 52, H 13, H 14, G 10, H 18; [14] H 12, H 13, H 16. — $>^{140}$Ba: [6] H 7; [13] H 7, H 9, H 52, H 13, H 14; [14] H 8, H 12, H 13. — $^{(138)}$La: [6] P 31; [8] P 31; [19] P 27, P 31, G 13a; [24] P 31. — ^{140}La: [6] H 18; [12] H 7, H 8, H 11, G 10, H 18; [13] H 7, H 8, H 11, H 13, H 14, G 10, H 18; [14] H 16; [21] M 8, H 18. — $>^{140}$La: [6] H 7; [12] H 7, H 11; [13] H 7, H 11, H 13, H 14, H 18; [14] H 8, H 13.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
58	**Ce**	**78**	**136**	rare	—	—	—	—	—	—
		80	**138**	rare	—	—	—	—	—	—
		81	139	—	2.1 *m*	β^+	—	—	—	—
		82	**140**	89	—	—	—	—	—	—
		83	141	—	15 *d*	β^-	—	0.12	—	—
		84	**142**	11	—	—	or —	—	—	—
		85	143	—	—	—	—	—	—	—
		?	?	—	~200 *d*	—	—	—	—	—
59	**Pr**	81	140	—	3.5 *m*	β^+	—	—	—	—
		82	**141**	100	—	—	—	—	—	—
		83	142	—	18.7 *h*	β^-	—	—	—	—
60	**Nd**	**82**	**142**	25.9_5	—	—	—	—	—	—
		83	**143**	13.0	—	—	—	—	—	—
		84	**144**	22.6	—	—	—	—	—	—
		85	**145**	9.2	—	—	—	—	—	—
		86	**146**	16.5	—	—	—	—	145.964	3
		87	147	—	(short?)	β^-	—	—	—	—
		88	**148**	6.8	—	—	or —	—	147.964	3
		89	149	—	—	—	—	—	—	—
		90	**150**	5.9_5	—	—	—	—	149.970	3
		(91)	(151)	—	?	(β^-)	—	—	—	—
61	—	(83)	(144)	—	108 *d*	—	—	—	—	—
		(86)	(147)	—	2.3 *h*	—	—	—	—	—
		(88)	(149)	—	—	—	or —	—	—	—
		(90)	(151)	—	?	(β^-)	—	—	—	—
62	**Sm**	**82**	**144**	. 3	—	—	—	—	—	—
		85	**147**	17	—	—	—	—	—	—
		86	*148*	14	$1.4 \cdot 10^{11}$ *a*	α	α : 2.4	—	—	—
		87	**149**	15	—	—	—	—	—	—
		88	**150**	3	—	—	—	—	—	—
		89	151	—	47 *h*	β^-	—	—	—	—
		90	**152**	26	—	—	or —	—	—	—
		91	153	—	21 *m*	β^-	—	—	—	—
		92	**154**	20	—	—	—	—	—	—
63	**Eu**	87	150	—	27 *h*	β^+	—	—	—	—
		88	**151**	49	—	—	—	0.123 ± 0.001,	—	—
		89	152	—	[9.4 ± 0.2] *h*	β^-, *K*	1.885 ± 0.012; 1.83	0.163 ± 0.001,	—	—
		(isomer)		—	[105 ± 5] *m*	—	—	0.725 ± 0.003	—	—
		90	**153**	51	—	—	—	—	—	—
		91	154	—	~1.2 *a*	β^-, (*K*)	or 1.0 ± 0.1; 0.8	—	—	—
		(isomer)		—	[12 ± 4) *m*	—	—	—	—	—
64	**Gd**	**88**	**152**	0.2	—	—	—	—	—	—
		90	**154**	1.5	—	—	—	—	—	—
		91	**155**	21	—	—	—	—	154.977	3.2
		92	**156**	22	—	—	—	—	155.977	3.0
		93	**157**	17	—	—	—	—	156.976	3.2

^{139}Ce: [6] P 31; [24] P 31. — $^{141, 143}$Ce: [6] R 31; [9] R 31; [13] H 18; [21] R 31. — ^{7}Ce: [6] H 18; [13] H 18. — ^{140}Pr: [6] P 31; [24] A 27, P 28, H 45, P 31. — ^{142}Pr: [6] P 31; [21] A 27, M 8, H 43, H 45, P 31; [23] P 28, P 31. — $^{147, 149}$Nd: [6] L 13b; [20] L 13b; [21] L 13b; [25] L 13b. — $^{(151)}$Nd: [20] L 13b; [21] L 13b. — $^{(144)}$61: [6] L 13b; [14] L 13b; [17] or [18] L 13b. — $^{(147, 149)}$61: [6] L 13b; [12] L 13b; [13] L 13b; [15] L 13b. — $^{(151)}$61: [12] L 13b. — ^{140}Sm: [6] H 64; [8] H 64. — ^{151}Sm: [6] L 13b; [12] L 13b;

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	Fission of		(p, γ)	(p, n)	$(d, 2n)$	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	$(n, 2n)$	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{136}Ce
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{138}Ce
—	—	—	—	—	—	—	—	—	—	—	—	$^{140}_{58}$Ce	—	^{139}Ce
—	—	—	—	—	—	—	—	—	$^{141}_{58}$Ce	or	—	$^{139}_{58}$Ce	—	^{140}Ce
—	($^{235}_{92}$U)	—	—	—	—	—	—	—	$^{140}_{58}$Ce		—	—	—	^{141}Ce
or	—	—	—	—	—	—	—	or	$^{143}_{58}$Ce		—	—	—	^{142}Ce
—	($^{235}_{92}$U)	—	—	—	—	—	—	—	$^{142}_{58}$Ce	—	—	—	—	^{143}Ce
—	($^{235}_{92}$U)	—	—	—	—	—	—	—	—	—	—	—	—	$^{?}$Ce
—	(α, p)	(α, n)	—	—	—	—	—	—	—	—	—	$^{141}_{59}$Pr	—	^{140}Pr
—	—	(^{144})61)	—	—	—	—	—	—	$^{143}_{59}$Pr	—	—	$^{140}_{59}$Pr	—	^{141}Pr
—	—	—	—	—	—	—	—	—	$^{141}_{59}$Pr	—	$^{142}_{60}$Nd	—	—	^{142}Pr
—	—	—	—	—	—	—	—	—	—	—	$^{142}_{59}$Pr	—	—	^{142}Nd
—	—	—	—	—	—	(^{144})61)	—	—	—	—	—	—	—	^{143}Nd
—	(^{147})61)	—	—	—	(^{144})61)	—	—	—	—	—	—	—	—	^{144}Nd
—	—	or	—	—	or	—	—	—	—	—	—	—	—	^{145}Nd
—	(^{149})61)	—	(^{147})61)	—	—	—	—	$^{147}_{60}$Nd	$^{147}_{60}$Nd	—	—	—	—	^{146}Nd
(^{147})61)	—	—	—	or	—	—	—	$^{148}_{60}$Nd	$^{148}_{60}$Nd	or	—	—	$^{148}_{60}$Nd	^{147}Nd
or	—	—	(^{149})61)	—	—	—	or	$^{149}_{60}$Nd	$^{149}_{60}$Nd	—	—	or	$^{147}_{60}$Nd	^{148}Nd
(^{149})61)	—	—	—	—	—	—	—	$^{150}_{60}$Nd	$^{150}_{60}$Nd	—	—	or	$^{150}_{60}$Nd	^{149}Nd
—	—	—	—	—	—	—	—	($^{151}_{60}$)Nd	($^{151}_{60}$)Nd	—	—	—	$^{149}_{60}$Nd	^{150}Nd
(^{151})61)	—	—	—	—	—	—	—	($^{150}_{60}$)Nd	($^{150}_{60}$)Nd	—	—	—	—	(^{151})Nd
—	—	($^{146}_{59}$Pr)	—	—	($^{146}_{60}$Nd)	($^{146}_{60}$Nd)	—	—	—	—	—	—	—	(^{144})61
($^{147}_{60}$Nd) or	($^{146}_{60}$Nd)	or	($^{146}_{60}$Nd)	or	—	or	—	—	—	—	—	—	—	(^{147})61
($^{149}_{60}$Nd)	($^{146}_{60}$Nd)		($^{146}_{60}$Nd)		—	—	—	—	—	—	—	—	—	(^{149})61
($^{151}_{60}$Nd)($^{151}_{62}$Sm)	—	—	—	—	—	—	—	—	—	—	—	—	—	(^{151})61
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{144}Sm
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{147}Sm
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{148}Sm
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{149}Sm
—	—	—	—	—	—	—	—	$^{151}_{62}$Sm	$^{151}_{62}$Sm	—	—	—	—	^{150}Sm
(^{151})61)	—	—	—	—	—	—	—	$^{150}_{62}$Sm	$^{150}_{62}$Sm	—	—	$^{152}_{62}$Sm	$^{152}_{62}$Sm	^{151}Sm
—	—	—	—	—	—	—	—	$^{153}_{62}$Sm	$^{153}_{62}$Sm	—	—	$^{151}_{62}$Sm	$^{151}_{62}$Sm	^{152}Sm
—	—	—	—	—	—	—	—	$^{152}_{62}$Sm	$^{152}_{62}$Sm	—	—	$^{154}_{62}$Sm	$^{154}_{62}$Sm	^{153}Sm
—	—	—	—	—	—	—	—	—	—	—	—	$^{153}_{62}$Sm	$^{153}_{62}$Sm	^{154}Sm
—	—	—	—	—	—	—	—	—	—	—	—	$^{151}_{63}$Eu	—	^{150}Eu
—	—	—	—	—	—	—	—	$^{152}_{63}$Eu	$^{152}_{63}$Eu	—	—	$^{150}_{63}$Eu	—	^{151}Eu
—	—	—	—	—	—	—	—	$^{151}_{63}$Eu	$^{151}_{63}$Eu	—	—	$^{153}_{63}$Eu	—	^{152}Eu
—	—	—	—	—	—	—	—	($^{151}_{63}$)Eu	—	—	—	—	—	(^{152})Eu*
—	—	—	—	—	—	—	—	($^{154}_{63}$)Eu*	$^{154}_{63}$Eu	—	—	$^{152}_{63}$Eu	—	^{153}Eu
—	—	—	—	—	—	—	—	—	$^{153}_{63}$Eu	—	—	—	—	^{154}Eu
—	—	—	—	—	—	—	—	($^{153}_{63}$)Eu	—	—	—	—	—	(^{154})Eu*
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{152}Gd
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{154}Gd
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{155}Gd
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{156}Gd
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{157}Gd

[20] L 13b; [21] M 8, H 45, P 31, L 13b; [24] P 31; [25] L 13b. — ^{139}Sm: [6] P 31; [20] L 13b; [21] A 27, M 8, M 18, H 43, H 44, P 31; [24] P 31; [25] L 13b. — ^{150}Eu: [6] P 31; [24] P 31. — ^{152}Eu: [6] F 3; [7] R 9; [8] T 13; F 3; [9] T 13; [20] F 3; [21] S 57, M 8, H 43, H 45, N 4, H 46, S 22, G 22, R 9, T 13, F 3, M 42; [24] P 31. — (^{152})Eu*: [3, 4] F 3; [6] F 3; [20] F 3. — ^{154}Eu: [6] S 22; [7] F 3; [8] F 3; R 31; [21] S 22, F 3, R 31. — (^{154})Eu*: [3, 4] F 3; [6] F 3; [20] F 3.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
64	Gd	**94**	**158**	22	—	—	—	—	157.976	3.3
		95	159	—	17 *h*	β^-	—	—	—	—
		(isomer)		—	3.5 *m*	β^-	—	—	—	—
		96	**160**	16	—	—	—	—	159.976	3.4
65	**Tb**	93	158	—	3.6 *m*	β^+	—	—	—	—
		94	**159**	100	—	—	—	—	—	—
		95	160	—	3.3 *h*	β^-	—	—	—	—
66	**Dy**	**92**	**158**	0.1	—	—	—	—	—	—
		93	159	—	2.2 *m*	β^+	—	—	—	—
		94	**160**	1.5	—	—	—	—	—	—
		95	**161**	22	—	—	—	—	—	—
		96	**162**	24	—	—	—	—	—	—
		97	**163**	24	—	—	—	—	—	—
		98	**164**	28	—	—	—	—	—	—
		99	165	—	[156 ± 3] *m*	β^-	1.67; 1.9; 1.4; *1.4*	(none)	—	—
67	**Ho**	97	164	—	47 *m*	β^-	—	—	—	—
		98	**165**	100	—	—	—	—	—	—
		99	166	—	30 *h*	β^-	1.6	—	—	—
68	**Er**	**94**	**162**	0.25	—	—	—	—	—	—
		96	**164**	2	—	—	—	—	—	—
		97	165	—	1.1 *m*	β^+	—	—	—	—
		98	**166**	(35)	—	—	—	—	—	—
		99	**167**	(24)	—	—	—	—	—	—
		100	**168**	(29)	—	—	—	—	—	—
		101	169	—	12 *h*	β^-	—	—	—	—
		102	**170**	(10)	—	—	—	—	—	—
		103	171	—	5.1 *h*	β^-	—	—	—	—
69	**Tm**	**100**	**169**	100	—	—	—	—	—	—
		101	170	—	[4 ± 1/2] *mo*	—	—	—	—	—
70	**Yb**	**98**	**168**	0.06	—	—	—	—	—	—
		100	**170**	4.21	—	—	—	—	—	—
		101	**171**	14.26	—	—	—	—	—	—
		102	**172**	21.49	—	—	—	—	—	—
		103	**173**	17.02	—	—	—	—	—	—
		104	**174**	29.58	—	—	—	—	—	—
		105	175	—	2.1 *h*	β^-	—	—	—	—
		(isomer)		—	41 *h*	β^-	—	—	—	—
		106	**176**	13.38	—	—	—	—	—	—
71	**Cp**	**104**	**175**	97.5	—	—	—	—	—	—
	(Lu)	*105*	*176*	2.5	[7.3 ± 2] · 10^{10} *a*	β^-	0.215 ± 0.015	—	—	—
		(105)	(176)	—	4 *h*	—	— or —	—	—	—
		(106)	(177)	—	6—7 *d*	—	—	—	—	—
72	**Hf**	**102**	**174**	(0.3)	—	—	—	—	—	—
		104	**176**	(5)	—	—	—	—	—	—
		105	**177**	(19)	—	—	—	—	—	—
		106	**178**	(28)	—	—	—	—	—	—

^{159}Gd: [6] P 31; [21] A 27, H 43, M 18, H 45, P 31; [23] P 31; [24] P 31. — $^{(159)}$Gd*: [3, 4] P 31; [6] P 31; [21] P 31; [23] P 31; [24] P 31. — ^{158}Tb: [6] P 31; [24] P 31. — ^{160}Tb: [6] P 31; [21] S 57, M 8, H 43, H 45, P 31. — ^{159}Dy: [6] P 31; [24] P 31. — ^{165}Dy: [6] M 31; [8] G 22; N 4; H 45; G 2; [9] M 42; [21] M 8, H 43, M 18, N 4, H 45, G 2, P 31, G 22, M 31, M 42. — ^{164}Ho: [6] P 31; [24] P 31. — ^{166}Ho: [6] P 31; [8] H 45; [21] H 44, N 6, H 45, P 31. — ^{165}Er: [6] P 31; [21] M 8, M 18; [24] P 21. — ^{169}Er: [6] P 31; [21] H 43, N 6,

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	(α, p)	(α, n)	(p, γ)	(p, n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	—	—	—	$^{158}_{64}$Gd	—	—	—	—	^{158}Gd
—	—	—	—	—	—	—	—	—	$^{158}_{64}$Gd	—	$^{159}_{65}$Tb	$^{159}_{64}$Gd	—	^{159}Gd
—	—	—	—	—	—	—	—	—	$^{158}_{64}$Gd	—	$^{159}_{65}$Tb	$^{159}_{64}$Gd	—	$^{(159)}$Gd*
—	—	—	—	—	—	—	—	—	—	—	—	$^{159}_{64}$Gd	—	^{160}Gd
—	—	—	—	—	—	—	—	—	—	—	—	$^{159}_{65}$Tb	—	^{158}Tb
—	—	—	—	—	—	—	—	—	$^{160}_{65}$Tb	—	$^{159}_{64}$Gd	$^{158}_{65}$Tb	—	^{159}Tb
—	—	—	—	—	—	—	—	—	$^{159}_{65}$Tb	—	—	—	—	^{160}Tb
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{158}Dy
—	—	—	—	—	—	—	—	—	—	—	—	$^{160}_{66}$Dy	—	^{159}Dy
—	—	—	—	—	—	—	—	—	—	—	—	$^{159}_{66}$Dy	—	^{160}Dy
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{161}Dy
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{162}Dy
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{163}Dy
—	—	—	—	—	—	—	—	—	$^{165}_{66}$Dy	—	—	—	—	^{164}Dy
—	—	—	—	—	—	—	—	—	$^{164}_{66}$Dy	—	—	—	—	^{165}Dy
—	—	—	—	—	—	—	—	—	—	—	—	$^{165}_{67}$Ho	—	^{164}Ho
—	—	—	—	—	—	—	—	—	$^{166}_{67}$Ho	—	—	$^{165}_{67}$Ho	—	^{165}Ho
—	—	—	—	—	—	—	—	—	$^{166}_{67}$Ho	—	—	—	—	^{166}Ho
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{162}Er
—	—	—	—	—	—	—	—	—	($^{165}_{68}$Er)	—	—	—	—	^{164}Er
—	—	—	—	—	—	—	—	—	($^{166}_{68}$Er)	—	—	$^{166}_{68}$Er	—	^{165}Er
—	—	—	—	—	—	—	—	—	$^{171}_{68}$Er	—	—	$^{165}_{68}$Er	—	^{166}Er
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{167}Er
—	—	—	—	—	—	—	—	—	$^{169}_{68}$Er	—	—	—	—	^{168}Er
—	—	—	—	—	—	—	—	—	$^{169}_{68}$Er	—	—	$^{170}_{68}$Er	—	^{169}Er
—	—	—	—	—	—	—	—	—	$^{171}_{68}$Er	—	—	$^{169}_{68}$Er	—	^{170}Er
—	—	—	—	—	—	—	—	—	$^{170}_{68}$Er	—	—	—	—	^{171}Er
—	—	—	—	—	—	—	—	—	$^{170}_{69}$Tm	—	—	—	—	^{169}Tm
—	—	—	—	—	—	—	—	—	$^{169}_{69}$Tm	—	—	—	—	^{170}Tm
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{168}Yb
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{170}Yb
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{171}Yb
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{172}Yb
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{173}Yb
—	—	—	—	—	—	—	—	—	$^{175}_{70}$Yb	—	—	—	—	^{174}Yb
—	—	—	—	—	—	—	—	—	$^{174}_{70}$Yb	—	—	$^{176}_{70}$Yb	—	^{175}Yb
—	—	—	—	—	—	—	—	—	$^{174}_{70}$Yb	—	—	$^{176}_{70}$Yb	—	$^{(175)}$Yb*
—	—	—	—	—	—	—	—	—	—	—	—	$^{175}_{70}$Yb	—	^{176}Yb
—	—	—	—	—	—	—	—	—	$^{(176)}_{71}$Cp	—	—	—	—	^{175}Cp
—	—	—	—	—	—	—	—	—	$^{(177)}_{71}$Cp	—	—	—	—	^{176}Cp
—	—	—	—	—	—	—	—	—	$^{(176)}_{71}$Cp	—	—	—	—	$^{(176)}$Cp
—	—	—	—	—	—	—	—	—	$^{(176)}_{71}$Cp	—	—	—	—	$^{(177)}$Cp
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{174}Hf
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{176}Hf
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{177}Hf
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{178}Hf

H 45, P 31; [24] P 31. — ^{171}Er: [6] P 31; [21] P 31. — ^{170}Tm: [6] N 7; [21] N 6, H 43, N 7, H 45, C 56. — ^{173}Yb: [6] P 31; [21] S 57, M 8, H 43, N 6, H 45, P 31; [24] P 31. — $^{(175)}$Yb*: [3, 4] P 31; [6] P 31; [21] N 6, P 31; [24] P 31. — ^{176}Cp: [6] L 17; [7] H 34, L 17; [8] L 17. — $^{(176)}$Cp: [6] H 45; [21] M 18, N 6, H 44, H 45. — $^{(177)}$Cp: [6] H 45; [21] H 44, H 45.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
72	Hf	**107**	**179**	(18)	—	—	—	—	—	—
		108	**180**	(30)	—	—	—	—	—	—
		109	181	—	[55 ± 7] *d*	β^-	—	—	—	—
73	**Ta**	107	180	—	[8.2 ± 0.2] *h*	*K*, (β^-)	(< 0.5)	—	—	—
		108	**181**	100	—	—	—	—	—	—
		109	182	—	[99 ± 1] *d*	β^-	1.0 ± 0.2; 1.1	—	—	—
74	**W**	**106**	**180**	0.2	—	—	—	—	—	—
		108	**182**	22.6	—	—	—	—	—	—
		109	**183**	17.3	—	—	—	—	—	—
		110	**184**	30.1	—	—	—	—	—	—
		111	185	—	[74.5 ± 1.5] *d*	β^-	0.64—0.72; 0.55—0.65; 0.4—0.5		—	—
		112	**186**	29.8	—	—	—	—	—	—
		113	187	—	[24.1 ± 0.1] *h*	β^-	1.40 ± 0.05; 1.1 ± 0.1	0.87 ± 0.03; 0.086, 0.101, 0.135	—	—
75	**Re**	109	184	—	[54 ± 2] *d*	(β^-, *K*)	—	0.17; 0.85 ± 0.1	—	—
		110	**185**	38.2	—	—	—	—	—	—
		111	186	—	[90 ± 2] *h*	β^-	1.05; *1.2*	(0.113, 0.129)	—	—
		112	**187**	61.8	—	—	—	—	—	—
		113	188	—	[16 ± 1] *h*	β^-	2.1; *2.5*	—	—	—
76	**Os**	**108**	**184**	0.018	—	—	—	—	—	—
		110	**186**	1.59	—	—	—	—	—	—
		111	**187**	1.64	—	—	—	—	—	—
		112	**188**	13.3	—	—	—	—	—	—
		113	**189**	16.2	—	—	—	—	—	—
		114	**190**	26.4	—	—	—	—	190.038	16.3
		115	191	—	[32 ± 2] *h*	β^-	1.5; ~1.0	—	—	—
		116	**192**	40.9	—	—	or —	—	192.038	6.3
		117	193	—	[17 ± 1] *d*	β^-	0.35	—	—	—
77	**Ir**	**114**	**191**	38.5	—	—	—	—	191.038	10.2
		(115)	(192)	—	68 *d*	β^-	—	—	—	—
		116	**193**	61.5	—	—	—	—	193.039	10.3
	[1]	(117)	(194)	—	1.5 *m*	β^-	—	—	—	—
	[2]	(117)	(194)	—	19.5 *h*	β^-	2.2; 2.1	—	—	—
78	**Pt**	**114**	**192**	0.8	—	—	—	—	—	—
		(115)	(193)	—	49 *m*	β^+	—	—	—	—
		116	**194**	30.2	—	—	—	—	194.039	6.4
		117	**195**	35.3	—	—	—	—	195.039	4.3
		118	**196**	26.6	—	—	—	—	196.039	8.1
		119	197	—	[19 ± 2] *h*	β^-	—	—	—	—
		(isomer)		—	3.3 *d*	β^-	—	—	—	—
		120	**198**	7.2	—	—	—	—	198.044	6.3
		121	199	—	[27 ± 5] *m*	β^-	—	—	—	—
		?	?	—	[85 ± 10] *m*	—	—	—	—	—

^{181}Hf: [6] H 46; [21] H 42, H 46. — ^{180}Ta: [6] O 2; [7] O 2; [8] O 2; [24] H 51, P 28, O 2, S 11. — ^{182}Ta: [6] H 65; [8] H 65; G 1; [20] O 2; [21] M 16, F 19, O 2, G 1, H 65. — ^{185}W: [6] F 5; [8] F 5; F 5; M 35; [19] F 5; [20] F 5; [21] M 35, F 5; [24] F 5. — ^{187}W: [6] F 5; [8] F 5; M 35; [9] F 5; V 3a; [20] F 5, V 3a; [21] A 27, M 16, J 2, M 35, F 5. — ^{184}Re: [6] C 49a; [7] F 5, C 49a; [9] C 49a; F 5; [16] C 49a; [17] or [18] F 5; [24] F 5. — ^{186}Re: [6] Y 1; [8] Y 1; Y 1, S 36; [9] V 3a; [16] C 49a; [17] F 5, V 3a; [20] F 5; [21] K 31, S 36, Y 1, F 5; [24] P 28, S 36, Y 1, F 5. — ^{188}Re: [6] Y 1; [8] Y 1; Y 1, S 36; [20] F 5; [21] A 27, K 31,

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	(α, p)	(α, n)	(p, γ)	(p, n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{179}Hf
—	—	—	—	—	—	—	—	—	$^{181}_{72}$Hf	—	—	—	—	^{180}Hf
—	—	—	—	—	—	—	—	—	$^{180}_{72}$Hf	—	—	—	—	^{181}Hf
—	—	—	—	—	—	—	—	—	—	—	—	$^{181}_{73}$Ta	—	^{180}Ta
—	—	—	—	—	—	—	—	($^{182}_{73}$Ta)	$^{182}_{73}$Ta	—	—	$^{180}_{73}$Ta	—	^{181}Ta
—	—	—	—	—	—	—	—	($^{181}_{73}$Ta)	$^{181}_{73}$Ta	—	—	—	—	^{182}Ta
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{180}W
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{182}W
—	—	—	—	—	—	or $^{184}_{75}$Re	—	—	—	—	—	—	—	^{183}W
—	—	—	—	—	$^{184}_{75}$Re	—	—	$^{185}_{74}$W	$^{185}_{74}$W	—	—	—	—	^{184}W
—	—	—	—	—	—	—	$^{187}_{75}$Re	$^{184}_{74}$W	$^{186}_{74}$W	—	—	($^{186}_{74}$W)	—	^{185}W
—	—	—	—	$^{186}_{75}$Re	$^{186}_{75}$Re	—	—	$^{187}_{74}$W	$^{187}_{74}$W	—	—	($^{185}_{74}$W)	—	^{186}W
—	—	—	—	—	—	—	—	$^{186}_{74}$W	$^{186}_{74}$W	—	—	—	—	^{187}W
—	—	—	—	$^{184}_{74}$W	$^{184}_{74}$ or	$^{186}_{74}$W	—	—	—	—	—	$^{188}_{75}$Re	—	^{184}Re
—	—	—	—	—	—	—	—	$^{186}_{75}$Re	$^{186}_{75}$Re	—	—	$^{184}_{75}$Re	—	^{185}Re
—	—	—	—	$^{186}_{74}$W	$^{186}_{74}$W	—	—	$^{185}_{75}$Re	$^{185}_{75}$Re	—	—	$^{187}_{75}$Re	—	^{186}Re
—	—	—	—	—	—	—	$^{185}_{74}$W	$^{188}_{75}$Re	$^{188}_{75}$Re	—	—	$^{186}_{75}$Re	—	^{187}Re
—	—	—	—	—	—	—	—	$^{187}_{75}$Re	$^{187}_{75}$Re	—	—	—	—	^{188}Re
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{184}Os
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{186}Os
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{187}Os
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{188}Os
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{189}Os
—	—	—	—	—	—	—	—	—	$^{191}_{76}$Os	—	—	—	—	^{190}Os
—	—	—	—	—	—	—	—	—	$^{190}_{76}$Os	—	—	($^{192}_{76}$Os)	—	^{191}Os
—	—	—	—	—	—	—	—	—	$^{193}_{76}$Os	—	—	($^{191}_{76}$Os)	—	^{192}Os
—	—	—	—	—	—	—	—	—	$^{192}_{76}$Os	—	—	—	—	^{193}Os
—	—	—	—	—	—	—	—	—	($^{192}_{77}$)Ir	—	—	—	—	^{191}Ir
—	—	—	—	—	—	—	—	—	($^{193}_{77}$)Ir	—	—	($^{193}_{77}$Ir)	—	(^{192})Ir
—	—	—	—	—	—	—	—	—	($^{194}_{77}$)Ir	—	—	($^{192}_{77}$Ir)	—	^{193}Ir
—	—	—	—	—	—	—	—	—	($^{192}_{77}$)Ir	—	—	—	—	(^{194})Ir^{1}
—	—	—	—	—	—	—	—	—	($^{193}_{77}$)Ir	—	—	—	—	(^{194})Ir^{2}
—	—	—	—	—	—	—	—	($^{193}_{78}$Pt)	—	—	—	—	—	^{192}Pt
—	—	—	—	—	—	—	—	($^{192}_{78}$Pt)	—	—	—	—	—	(^{193})Pt
—	—	—	—	—	—	$^{195}_{79}$Au	—	—	—	—	—	—	—	^{194}Pt
—	—	—	—	—	—	($^{196}_{79}$)Au*	—	—	—	—	—	—	—	^{195}Pt
—	—	—	—	—	—	($^{197}_{79}$)Au*	—	$^{197}_{78}$Pt	$^{197}_{78}$Pt	—	—	—	—	^{196}Pt
—	—	—	—	—	—	—	—	$^{196}_{78}$Pt	$^{198}_{78}$Pt	$^{200}_{80}$Hg	—	—	—	^{197}Pt
—	—	—	—	—	—	—	—	—	($^{196}_{78}$)Pt	($^{200}_{80}$Hg)	—	—	—	(^{197})Pt*
—	—	—	—	—	$^{198}_{79}$Au	($^{199}_{79}$)Au	—	($^{198}_{78}$Pt)	$^{198}_{78}$Pt	—	—	—	—	^{198}Pt
$^{199}_{79}$Au	—	—	—	—	—	—	—	($^{198}_{78}$Pt)	$^{198}_{78}$Pt	$^{202}_{80}$Hg	—	—	—	^{199}Pt
—	—	—	—	—	—	—	—	—	—	$^{?}_{80}$Hg	—	—	—	$^{?}$Pt

P 28, S 36, Y 1, F 5. — ^{191}Os: [6] S 27c; [8] S 27c; Z 1; [21] K 31, Z 1, S 27c; [24] S 27c. — ^{192}Os: [6] S 27c; [8] S 27c; [21] Z 1, S 27c. — (^{192})Ir: [6] J 3; [21] F 19, M 23, J 3; [24] M 23. — (^{194})Ir^{1}: [6] M 23; [21] M 23. — (^{194})Ir^{2}: [6] J 3; [8] A 8; M 23; [21] A 27, A 12, A 8, M 23, J 3. — (^{193})Pt: [6] C 29; [20] C 29. — ^{197}Pt: [6] S 34a; [20] C 29; [21] M 23; [22] S 34a. — (^{197})Pt*: [3, 4] M 23; [6] M 23; [21] M 23; [22] S 34a. — ^{199}Pt: [6] M 23; [20] C 29; [21] A 27, M 16, M 23; [22] S 34a. — $^{?}$Pt: [6] S 34a; [22] S 34a.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Energy of Radiation MeV β	Energy of Radiation MeV γ	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
79	**Au**	116	195	—	37 *m*	β^+	—	—	—	—
		(isomer)		—	54 *h*	(γ)	—	0.55	—	—
		(117)	(196)	—	13 *h*	β^-	or —	—	—	—
		(isomer)		—	—	—	—	—	—	—
		118	**197**	100	—	—	or —	—	197.039	5.9
		(isomer)		—	5.6 *d*	γ	—	0.356 ± 0.004	—	—
		119	198	—	2.72 *d*	β^-, (*K*)	0.77; 0.74; 0.83; 0.78	0.07, 0.28, 0.43; 0.073, 0.23, 0.41, 2.5; 0.331 ± 0.003, 0.410 ± 0.004	—	—
		120	199	—	3.3 *d*	β^-	—	—	—	—
		(120)	(199)	—	164 *d*	β^-	0.45	0.11	—	—
		?	?	—	[48 ± 1] *m*	—	—	—	—	—
80	**Hg**	**116**	**196**	0.15	—	—	—	—	—	—
		117	197	—	[43 ± 1] *m*	*K*	—	0.07—0.25	—	—
		118	**198**	10.12	—	—	—	—	—	—
		119	**199**	17.04	—	—	—	—	—	—
		120	**200**	23.25	—	—	—	—	—	—
		121	**201**	13.18	—	—	—	—	—	—
		122	**202**	29.54	—	—	—	—	—	—
		123	203	—	25 *h*	—	—	—	—	—
		124	**204**	6.72	—	—	or —	—	—	—
		125	205	—	—	—	—	—	—	—
		?	?	—	> 30 *d*	—	—	—	—	—

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Decay Energy MeV β	Decay Energy MeV α	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
81	**Tl**	**122**	**203**	29.1	—	—	—	—	203.059	9.2
		123	204	—	[4.23 ± 0.03] *m*	β^-	1.6 ± 0.1	—	—	—
		124	**205**	70.9	—	—	—	—	205.059	9.2
		125	206	—	1 to 2 *a*	—	—	—	—	—
	AcC″	*126*	*207*	—	[4.76 ± 0.02] *m*	β^-	1.47	—	—	—
	ThC″	*127*	*208*	—	3.1 *m*	β^-	1.82	—	—	—
	RaC″	*129*	*210*	—	1.32 *m*	β^-	1.8	—	—	—
82	**Pb**	**122**	**204**	1.5	—	—	—	—	—	—
		(isomer)		—	[52 ± 1] *h*	—	(γ: ~0.5)	—	—	—
		(123)	(205)	—	80 *m*	—	—	—	—	—
	RaG	**124**	**206**	23.6	—	—	or —	—	204.061	9.2
		(isomer)		—	—	—	—	—	—	—
	AcD	**125**	**207**	22.6	—	—	—	—	—	—
	ThD	**126**	**208**	52.3	—	—	—	—	208.060	9.0
		127	209	—	3.3 *h*	β^-	—	—	—	—
	*	?	? *)	—	[1.6 ± 0.2] *m*	γ	γ: ~ 0.15—0.25	—	—	—
	RaD	*128*	*210*	—	22 *a*	β^-	0.0255 ± 0.001	—	—	—

^{195}Au: [6] C 35; [18] C 35, L 23. — $^{(195,196)}$Au*: [6] C 35; [7] C 35; [9] C 35; [18] C 35. — $^{(196)}$Au: [6] M 23; [24] M 23. — $^{(196,197)}$Au*: [3, 4] M 23, L 23; [6] C 35; [7] L 23; [9] L 23; [18] C 35, L 23; [24] or [25] M 23. — ^{198}Au: [6] S 37; [7] S 37; [8] L 30; C 35; R 9, S 37; M 23; [9] R 9; S 37; L 23; [17] C 35, L 23; [20] C 30, N 14; [21] A 27, K 31, E 6, A 12, A 8, M 23, L 30, R 9, S 37, W 17a; [23] S 34a. — ^{199}Au: [6] M 23; [12] M 23; [23] S 34a. — $^{(199)}$Au: [6] C 35; [8] C 35; [9] C 35; [18] C 35, L 23. — ^{1}Au: [6] S 34a; [23] S 34a. — ^{197}Hg: [6] H 51; [7] A 21, R 31; [9] M 23; [24] H 51, P 28, M 23, A 21, R 31, S 34a. — ^{203,205}Hg: [6] M 23; [21]

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay	(α, p)	(α, n)	(p, γ)	(p, n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
12	13	14	15	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	—	$^{194}_{78}$Pt	—	—	—	—	—	—	—	^{195}Au
—	—	—	—	—	—	$^{194}_{78}$Pt	—	—	—	—	—	—	—	$^{(195)}$Au*
—	—	—	—	—	or	—	—	—	—	—	—	$^{(197}_{79}$Au)		$^{(196)}$Au
—	—	—	—	—	—	$^{195}_{78}$Pt	—	—	—	—	—	$^{197}_{79}$Au	(n, n)	$^{(196)}$Au*
—	—	—	—	—	or	—	—	$^{198}_{79}$Au	$^{198}_{79}$Au	—	or	$^{(196)}_{79}$Au or	$^{(197)}_{79}$Au*	^{197}Au
—	—	—	—	—	—	$^{196}_{78}$Pt	—	—	—	—			$^{197}_{79}$Au	$^{(197)}$Au*
—	—	—	—	—	$^{198}_{78}$Pt	—	—	$^{197}_{79}$Au	$^{197}_{79}$Au	—	$^{198}_{80}$Hg	—	—	^{198}Au
$^{199}_{78}$Pt	—	—	—	—	—	—	—	—	—	—	$^{199}_{80}$Hg	—	—	^{199}Au
—	—	—	—	—	—	$^{198}_{78}$Pt	—	—	—	—	—	—	—	$^{(199)}$Au
—	—	—	—	—	—	—	—	—	—	—	$^{?}_{80}$Hg	—	—	$^{?}$Au
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{196}Hg
—	—	—	—	—	—	—	—	—	—	—	—	$^{198}_{80}$Hg	—	^{197}Hg
—	—	—	—	—	—	—	—	—	—	—	$^{198}_{79}$Au	$^{197}_{80}$Hg	—	^{198}Hg
—	—	—	—	—	—	—	—	—	—	—	$^{199}_{79}$Au	—	—	^{199}Hg
—	—	—	—	—	—	—	—	—	—	$^{197}_{78}$Pt	—	—	—	^{200}Hg
—	—	—	—	—	—	—	—	—	—	—	—	—	—	^{201}Hg
—	—	—	—	—	—	—	—	—	$^{203}_{80}$Hg	$^{199}_{78}$Pt	—	—	—	^{202}Hg
—	—	—	—	—	—	—	—	—	$^{203}_{80}$Hg	or	—	—	—	^{203}Hg
—	—	—	—	—	—	—	—	or	$^{205}_{80}$Hg	—	—	—	—	^{204}Hg
—	—	—	—	—	—	—	—	—	$^{204}_{80}$Hg	—	—	—	—	^{205}Hg
—	—	—	—	—	—	—	—	—	$^{?}_{80}$Hg	or	—	$^{?}_{80}$Hg	—	$^{?}$Hg

Radioactive Decay			(α, 2n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
β	α	K											
12	13	14	16	17	18	19	20	21	22	23	24	25	
—	—	—	—	—	$(^{204}_{82}$Pb*)	—	$^{204}_{81}$Tl	$^{204}_{81}$Tl	—	—	—	—	^{203}Tl
—	—	—	—	—	—	or	$^{203}_{81}$Tl	$^{203}_{81}$Tl	—	—	$^{205}_{81}$Tl	—	^{204}Tl
—	—	—	—	—	$(^{206}_{82}$Pb*)	—	$^{206}_{81}$Tl	$^{206}_{81}$Tl	—	—	$^{204}_{81}$Tl	—	^{205}Tl
—	—	—	—	—	—	—	$^{205}_{81}$Tl	$^{205}_{81}$Tl	—	—	—	—	^{206}Tl
$^{207}_{82}$Pb	$^{211}_{83}$Bi	—	—	—	—	—	—	—	—	$^{207}_{82}$Pb	—	—	^{207}Tl
$^{208}_{82}$Pb	$^{212}_{83}$Bi	—	—	—	—	—	—	—	—	—	—	—	^{208}Tl
$^{210}_{82}$Pb	$^{214}_{83}$Bi	—	—	—	—	—	—	—	—	—	—	—	^{210}Tl
—	—	—	—	—	—	—	—	—	—	—	—	—	^{204}Pb
—	—	—	—	—	$(^{203}_{81}$Tl)	—	—	—	—	—	—	—	$^{(204)}$Pb*
—	—	—	—	—	—	—	—	—	—	—	$^{(206)}_{82}$Pb	—	$^{(205)}$Pb
—	—	—	—	or	—	—	—	—	—	—	$^{(205)}_{82}$Pb	—	^{206}Pb
—	—	—	—	—	$(^{205}_{81}$Tl)	—	—	—	—	—	—	—	$^{(206)}$Pb*
$^{207}_{81}$Tl	—	—	—	—	—	—	—	—	—	$^{207}_{81}$Tl	—	—	^{207}Pb
$^{209}_{81}$Tl	—	—	—	—	—	—	$^{208}_{82}$Pb	$^{208}_{82}$Pb	—	—	—	—	^{208}Pb
—	—	—	—	—	—	—	$^{209}_{82}$Pb	$^{208}_{82}$Pb	—	$^{209}_{83}$Bi	—	$(\gamma, —)$	^{209}Pb
—	—	—	—	—	—	—	—	—	—	—	—	$^{?}_{82}$Pb	$^{?}$Pb*
$^{210}_{81}$Tl	$^{210}_{83}$Bi	—	—	—	—	—	—	—	—	—	—	—	^{210}Pb

A 27, R 3, A 29, F 18, M 23, S 34a. — $^{?}$Hg: [6] S 34a; [21] or [24] S 34a. — ^{204}Tl: [6] F 4; [8] F 4; [20] F 4; [21] P 34, F 4, B 58b; [24] H 51, P 28, F 4. — ^{205}Tl: [6] F 4; [20] F 4; [23] F 4. — ^{207}Tl: [6] S 17; [8] S 16; [23] B 58b. — ^{208}Tl: [8] see S 15. — ^{210}Tl: [8] L 25. — $^{(204, 206)}$Pb*: [3, 4] F 4; [6] F 4; [8] F 4; [18] F 4. — $^{(205)}$Pb: [6] V 12; [24] V 12. — ^{209}Pb: [6] M 11b; [20] T 7; [21] M 11b; [23] M 11b. — $^{?}$Pb*: [3, 4] *) isomer of a stable Pb nucleus: W 1a, C 27a; [6] W 1a; [7] W 1a; [8] W 1a; [25] W 1a, C 27a. — ^{210}Pb: [8] L 26.

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Z	Symbol	N	A	Abundance in %	Half-life	Decay	Decay Energy MeV β	Decay Energy MeV α	Isotopic Weight M MU	Error of M 10^{-3} MU
1	2	3	4	5	6	7	8	9	10	11
82	AcB	*129*	*211*	—	[36.1 ± 0.2] *m*	β^-	0.5, 1.39	—	—	—
	ThB	*130*	*212*	—	10.6 *h*	β^-	0.362	—	—	—
	RaB	*132*	*214*	—	26.8 *m*	β^-	0.65	—	—	—
83	**Bi**	**126**	**209**	100	—	—	—	—	209.056	8.6
	RaE	*127*	*210*	—	5.0 *d*	β^-	1.170	—	—	—
	AcC	*128*	*211*	—	2.16 *m*	β^-, α	[0.32%]	[99.68%] 6.739	—	—
	ThC	*129*	*212*	—	60.5 *m*	β^-, α	[65%] 2.20	[35%] 6.200_{69}	—	—
	RaC	*131*	*214*	—	19.7 *m*	β^-, α	[99.96%] 3.15	[0.04%] 5.611_7	—	—
84	**Po**RaF	*126*	*210*	—	140 *d*	α	—	5.403_3	—	—
	AcC′	*127*	*211*	—	$\sim 5 \cdot 10^{-3}$ *s*	α	—	7.581	—	—
	ThC′	*128*	*212*	—	$[3 \pm 1] \cdot 10^{-7}$ *s*	α	—	8.947_6	—	—
	RaC′	*130*	*214*	—	$[1.50 \pm 0.20] \cdot 10^{-4}$ *s*	α	—	7.829_{34}	—	—
	AcA	*131*	*215*	—	$2 \cdot 10^{-3}$ *s*	α	—	7.508	—	—
	ThA	*132*	*216*	—	0.14 *s*	α	—	6.903_8	—	—
	RaA	*134*	*218*	—	3.05 *m*	α	—	6.1123_9	—	—
85	—	126	211	—	7.5 *h*	*K*, α	*K*: [60%]	[40%] 6.05	—	—
86	An	*133*	*219*	—	3.92 *s*	α	—	6.953	—	—
	Tn	*134*	*220*	—	54.5 *s*	α	—	6.399_5	—	—
	Rn	*136*	*222*	—	3.825 *d*	α	—	5.5886_7	—	—
87	AcK	*136*	*223*	—	[21 ± 1] *m*	β^-	1.2	—	—	—
88	AcX	*135*	*223*	—	11.4 *d*	α	—	5.823	—	—
	ThX	*136*	*224*	—	3.64 *d*	α	—	5.7858	—	—
	Ra	*138*	*226*	—	1590 *a*	α	—	4.879	—	—
	$MsTh_1$	*140*	*228*	—	6.7 *a*	β^-	0.053 ± 0.004	—	—	—
89	**Ac**	*138*	*227*	—	13.5 *a*	β^-, α	[99%] 0.220 ± 0.05	[1%] 5.10	—	—
	$MsTh_2$	*139*	*228*	—	6.13 *h*	β^-	1.55 ± 0.07	—	—	—
90	RdAc	*137*	*227*	—	18.9 *d*	α	—	6.159	—	—
	RdTh	*138*	*228*	—	1.90 *a*	α	—	5.517	—	—
	Io	*140*	*230*	—	$8.3 \cdot 10^4$ *a*	α	—	4.76	—	—
	UY	*141*	*231*	—	24.6 *h*	β^-	—	—	—	—
	Th	*142*	*232*	100	$1.39 \cdot 10^{10}$ *a*	α	—	4.28	—	—
	—	143	233	—	23.0 *m*	β^-	—	—	—	—
	UX_1	*144*	*234*	—	[24.1 ± 0.2] *d*	β^-	(0.265); (0.13)	—	—	—
91	**Pa**	*140*	*231*	—	$3.2 \cdot 10^4$ *a*	α	—	5.142	—	—
	—	142	233	—	[27.4 ± 0.4] *d*	β^-	0.23; 0.4	—	—	—
	UZ	*143*	*234*	—	6.7 *h*	β^-	0.56, 1.55	—	—	—
	UX_2	*isomer*		—	1.14 *m*	β^-, γ	[99.85%] 2.32; 5% 1.52, 95% 2.32	γ: [0.15%]	—	—
92	U II	*142*	*234*	0.006	$2.7 \cdot 10^5$ *a*	α	—	4.79	—	—
	AcU	*143*	*235*	0.720	$7.13 \cdot 10^8$ *a*	α	—	4.59	—	—
	—	145	237	—	[7.0 ± 0.2] *d*	β^-	0.26; 0.2	—	—	—
	U I	*146*	*238*	99.274	$4.56 \cdot 10^9$ *a*	α	—	4.21	—	—
	—	147	239	—	23.5 *m*	β^-	—	—	—	—
93	—	146	239	—	2.3 *d*	β^-	0.47	γ: 0.22, 0.27	—	—

^{211}Pb: [6] S 17; [8] S 16. — ^{212}Pb: [8] see S 15 also O 8. — ^{214}Pb: [8] see S 15. — ^{210}Bi: [8] F 17, N 5; [20] L 33, H 71, C 34; [21] M 11b. — ^{212}Bi: [8] see S 15. — ^{214}Bi: [8] see S 15. — ^{210}Po: [12] L 33, H 71; [18] H 71, C 34. — ^{211}Po: [14] C 37, C 37a. — ^{212}Po: [6] D 36. — ^{214}Po: [6] D 36, R 28. — ^{211}85: [6] C 37, C 37a; [7] C 37, C 37a; [9] C 37a; [16] C 37, C 37a. — ^{223}AcK: [6] P 4; [8] P 5, P 6; [13] M 33, P 4. — ^{223}Ra: [12] P 6. — ^{226}Ra: [8] L 26. — ^{227}Ac: [8] H 68; [9] P 6. — ^{228}Ac: [8] L 30. — ^{230}Th: [9] G 5a, W 20a. — ^{231}Th: [24] N 18. — ^{232}Th: [6] K 23; [9] S 22a. — ^{233}Th: [6] G 20a; M 30; [21] F 14, H 4, A 27, M 30, S 27b, G 20a.

In columns 12 to 25 red print represents the initial product, and black print, the end product of a reaction. The other reaction member is the isotope given in sans serif type at the beginning and end of the row.

Radioactive Decay			(α, 2n)	(d, 2n)	(d, n)	(d, α)	(d, p)	(n, γ)	(n, α)	(n, p)	(n, 2n)	(γ, n)	
β	α	K											
12	13	14	16	17	18	19	20	21	22	23	24	25	
$^{211}_{83}$Bi	$^{215}_{84}$Po	—	—	—	—	—	—	—	—	—	—	—	^{211}Pb
$^{212}_{83}$Bi	$^{216}_{84}$Po	—	—	—	—	—	—	—	—	—	—	—	^{212}Pb
$^{214}_{83}$Bi	$^{218}_{84}$Po	—	—	—	—	—	—	—	—	—	—	—	^{214}Pb
—	—	—	$^{211}_{85}$	—	$^{210}_{84}$Po	—	$^{210}_{83}$Bi	$^{210}_{83}$Bi	—	$^{209}_{82}$Pb	—	—	^{209}Bi
$^{210}_{82}$Pb $^{210}_{84}$Po	—	—	—	—	—	—	$^{209}_{83}$Bi	$^{209}_{83}$Bi	—	—	—	—	^{210}Bi
$^{211}_{82}$Pb $^{211}_{84}$Po	$^{207}_{81}$Tl	—	—	—	—	—	—	—	—	—	—	—	^{211}Bi
$^{212}_{82}$Pb $^{212}_{84}$Po	$^{208}_{81}$Tl	—	—	—	—	—	—	—	—	—	—	—	^{212}Bi
$^{214}_{82}$Pb $^{214}_{84}$Po	$^{210}_{81}$Tl	—	—	—	—	—	—	—	—	—	—	—	^{214}Bi
$^{210}_{83}$Bi	$^{204}_{81}$Pb	—	—	—	$^{209}_{83}$Bi	—	—	—	—	—	—	—	^{210}Po
$^{211}_{83}$Bi	$^{207}_{82}$Pb	$^{211}_{85}$	—	—	—	—	—	—	—	—	—	—	^{211}Po
$^{212}_{83}$Bi	$^{208}_{82}$Pb	—	—	—	—	—	—	—	—	—	—	—	^{212}Po
$^{214}_{83}$Bi	$^{210}_{82}$Pb	—	—	—	—	—	—	—	—	—	—	—	^{214}Po
—	$^{219}_{86}$Rn $^{211}_{82}$Pb		—	—	—	—	—	—	—	—	—	—	^{215}Po
—	$^{220}_{86}$Rn $^{212}_{82}$Pb	—	—	—	—	—	—	—	—	—	—	—	^{216}Po
—	$^{222}_{86}$Rn $^{214}_{82}$Pb	—	—	—	—	—	—	—	—	—	—	—	^{218}Po
—	($^{207}_{83}$Bi)	$^{211}_{84}$Po	$^{209}_{83}$Bi	—	—	—	—	—	—	—	—	—	$^{211}_{85}$
—	$^{223}_{88}$Ra $^{215}_{84}$Po	—	—	—	—	—	—	—	—	—	—	—	^{219}Rn
—	$^{224}_{88}$Ra $^{216}_{84}$Po	—	—	—	—	—	—	—	—	—	—	—	^{220}Rn
—	$^{226}_{88}$Ra $^{218}_{84}$Po	—	—	—	—	—	—	—	—	—	—	—	^{222}Rn
$^{223}_{88}$Ra	$^{227}_{89}$Ac	—	—	—	—	—	—	—	—	—	—	—	^{223}Ac K
$^{223}_{87}$Ac K	$^{227}_{90}$Th $^{219}_{86}$Rn	—	—	—	—	—	—	—	—	—	—	—	^{223}Ra
—	$^{228}_{90}$Th $^{220}_{86}$Rn	—	—	—	—	—	—	—	—	—	—	—	^{224}Ra
—	$^{230}_{90}$Th $^{222}_{86}$Rn	—	—	—	—	—	—	—	—	—	—	—	^{226}Ra
$^{228}_{89}$Ac	$^{232}_{90}$Th		—	—	—	—	—	—	—	—	—	—	^{228}Ra
$^{227}_{90}$Th	$^{231}_{91}$Pa $^{223}_{87}$Ac K	—	—	—	—	—	—	—	—		—		^{227}Ac
$^{228}_{88}$Ra $^{228}_{90}$Th		—	—	—	—	—	—	—	—		—	—	^{228}Ac
$^{227}_{89}$Ac	$^{223}_{88}$Ra	—	—	—	—	—	—	—	—	—	—	—	^{227}Th
$^{228}_{89}$Ac	$^{224}_{88}$Ra	—	—	—	—	—	—	—	—	—	—	—	^{228}Th
—	$^{234}_{92}$U $^{226}_{88}$Ra	—	—	—	—	—	—	—	—	—	—	—	^{230}Th
$^{231}_{91}$Pa	$^{235}_{92}$U	—	—	—	—	—	—	—	—	—	$^{228}_{90}$Th	—	^{231}Th
—	$^{228}_{88}$Ra	—	—	—	—	—	—	$^{232}_{90}$Th	—	—	$^{231}_{90}$Th	—	^{232}Th
$^{233}_{91}$Pa	—	—	—	—	—	—	—	$^{232}_{90}$Th	—	—	—	—	^{233}Th
$^{234}_{91}$Pa*	$^{238}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	^{234}Th
$^{231}_{90}$Th	$^{227}_{89}$Ac	γ	—	—	—	—	—	—	—	—	—	—	^{231}Pa
$^{233}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	—	^{233}Pa
$^{234}_{92}$U	—	$^{234}_{91}$Pa*	—	—	—	—	—	—	—	—	—	—	^{234}Pa
$^{234}_{90}$Th $^{234}_{92}$U	—	$^{234}_{91}$Pa	—	—	—	—	—	—	—	—	—	—	^{234}Pa*
$^{234}_{91}$Pa; $^{234}_{91}$Pa*	$^{230}_{90}$Th	—	—	—	—	—	—	—	—	—		—	^{234}U
—	$^{234}_{90}$Th	—	—	—	—	—	—	—	—	—	—	—	^{235}U
—	—	—	—	—	—	—	—	—	—	—	$^{238}_{92}$U	—	^{237}U
—	$^{234}_{90}$Th	—	—	—	—	—	—	$^{238}_{92}$U	—	—	$^{237}_{92}$U	—	^{238}U
$^{239}_{93}$	—	—	—	—	—	—	—	$^{238}_{92}$U	—	—	—	—	^{239}U
$^{239}_{92}$U	—	—	—	—	—	—	—	—	—	—	—	—	$^{239}_{93}$

— ^{234}Th: [6] S 17; [8] M 8a; see S 15. — ^{231}Pa: [9] R 17a. — ^{233}Pa: [6] G 20a; [8] H 2a; S 27b; [12] M 30, H 19b, S 27b, H 2a, G 20a. — ^{234}Pa: [8] F 10; [14] F 10. — ^{234}Pa*: [3, 4] H 3, F 10, F 12; [7] F 10; [8] S 15; M 8a; [9] F 10. — ^{234}U: [6] N 15; [9] R 3a; [12] H 3, F 10. — ^{235}U: [6] N 15; [9] W 18a. — ^{237}U: [6] M 26; [8] M 26; Y 3; [24] N 19, Y 3, M 26. — ^{238}U: [6] N 15; [9] R 3a. — ^{239}U: [6] G 20; [21] H 5, M 29, M 24, S 31, M 25, M 26, B 42, G 20a. — ^{239}93: [6] M 25; [8] M 25; [9] H 31a; [12] M 24, S 31, M 25, M 26

For each isotope the literature references apply to the entries identified by the column numbers in [ ]; since all reactions appear twice, references for columns 12 to 25 pertain to the red print.

Fission Products of:

$^{232}_{90}$**Th**	$^{83}_{35}Br \rightarrow {}^{83}_{36}Kr^*$, $>{}^{82}_{35}Br^1$, $^{88}_{36}Kr \rightarrow {}^{88}_{37}Rb$, $^{(91)}_{36}Kr \rightarrow {}^{(91)}_{37}Rb\ (\rightarrow)\ {}^{(91)}_{38}Sr \rightarrow {}^{(91)}_{39}Y$, $^{95}_{40}Zr \rightarrow {}^{95}_{41}Nb$, $(^{?}_{40}Zr)$, $^{99}_{42}Mo \rightarrow {}^{99}43^*$, $>{}^{105}_{44}Ru$, $^{111}_{46}Pd \rightarrow {}^{111}_{47}Ag$, $^{112}_{46}Pd \rightarrow {}^{112}_{47}Ag$, $>{}^{131}_{52}Te^1 \rightarrow >{}^{131}_{53}I^1$, $^{(133)}_{51}Sb\ (\rightarrow)\ {}^{133}_{52}Te \rightarrow {}^{133}_{53}I \rightarrow {}^{133}_{54}X$, $>{}^{131}_{52}Te^2 \rightarrow$ $\rightarrow >{}^{131}_{53}I^2$, $^{135}_{52}Te \rightarrow {}^{135}_{53}I \rightarrow {}^{135}_{54}X^*$, $>{}^{136}_{54}X \rightarrow >{}^{136}_{55}Cs$, $^{139}_{54}X \rightarrow {}^{139}_{55}Cs \rightarrow {}^{139}_{56}Ba$, $^{(140)}_{54}X \rightarrow {}^{(140)}_{55}Cs\ (\rightarrow)\ {}^{140}_{56}Ba \rightarrow$ $\rightarrow {}^{140}_{57}La$, $>{}^{140}_{56}Ba \rightarrow >{}^{140}_{57}La$.
$^{231}_{91}$**Pa**	$^{88}_{37}Rb$, $>{}^{136}_{57}Cs$.
$^{235}_{92}$**U**	$^{83}_{35}Br \rightarrow {}^{83}_{36}Kr^*$ $>{}^{82}_{35}Br^1$, $>{}^{82}_{35}Br^2$, $>{}^{82}_{35}Br^3$, $^{88}_{36}Kr \rightarrow {}^{88}_{37}Rb$, $^{89}_{36}Kr \rightarrow {}^{89}_{37}Rb \rightarrow {}^{89}_{38}Sr$, $^{(91)}_{36}Kr \rightarrow {}^{(91)}_{37}Rb\ (\rightarrow)\ {}^{(91)}_{38}Sr \rightarrow$ $\rightarrow {}^{(91)}_{39}Y$, $>{}^{91}_{36}Kr \rightarrow >{}^{91}_{37}Rb \rightarrow >{}^{91}_{38}Sr \rightarrow >{}^{91}_{39}Y^* \rightarrow >{}^{91}_{39}Y$, $^{90}_{38}Sr \rightarrow {}^{90}_{39}Y$, $^{?}_{38}Sr$, $^{95}_{40}Zr \rightarrow {}^{95}_{41}Nb$ [6.1%] [1]), $^{?}_{40}Zr$, $^{99}_{42}Mo \rightarrow {}^{99}43^*$, $^{101}_{42}Mo \rightarrow {}^{101}43$, $>{}^{101}_{42}Mo\ (\rightarrow >{}^{101}43)$, $^{127}_{51}Sb \rightarrow {}^{127}_{52}Te$ [0.18%] [1]), $^{129}_{51}Sb \rightarrow {}^{129}_{52}Te$ [0.34%] [1]), $>{}^{131}_{51}Sb \rightarrow >{}^{131}_{52}Te^1 \rightarrow >{}^{131}_{53}I^1$ [5.2%] [1]), $^{(133)}_{51}Sb\ (\rightarrow)\ {}^{133}_{52}Te \rightarrow {}^{133}_{53}I \rightarrow {}^{133}_{54}X$ [7.6%] [1]), $^{131}_{52}Te^* \rightarrow {}^{131}_{52}Te \rightarrow {}^{131}_{53}I$ [1.6%] [1]), $>{}^{131}_{52}Te^2 \rightarrow >{}^{131}_{53}I^2$ [12%] [1]), $^{135}_{52}Te \rightarrow {}^{135}_{53}I \rightarrow {}^{135}_{54}X^* \rightarrow {}^{135}_{54}X$ [9.0% ?] [1]), $>{}^{131}_{53}I^3$, $>{}^{131}_{53}I^4$, $>{}^{136}_{54}X \rightarrow$ $\rightarrow >{}^{136}_{55}Cs$, $^{139}_{54}X \rightarrow {}^{139}_{55}Cs \rightarrow {}^{139}_{56}Ba$ [6.4%] [1]), $^{(140)}_{54}X \rightarrow {}^{(140)}_{55}Cs\ (\rightarrow)\ {}^{140}_{56}Ba \rightarrow {}^{140}_{57}La$ [8.4%] [1]), $>{}^{140}_{56}Ba \rightarrow >{}^{140}_{57}La$, $(^{141,\ 143}_{58}Ce)$, $(^{?}_{58}Ce)$.
$^{238}_{92}$**U**	(besides an undetermined number of the above) $>{}^{105}_{44}Ru \rightarrow >{}^{105}_{45}Rh$, $^{111}_{46}Pd \rightarrow {}^{111}_{47}Ag$, $^{112}_{46}Pd \rightarrow {}^{112}_{47}Ag$, $^{115}_{48}Cd \rightarrow {}^{115}_{49}In^*$, $^{117}_{48}Cd \rightarrow {}^{117}_{49}In$, $^{?}_{48}Cd^*$.

[1]) Per cent of total fission activity according to A 31a.

Table V

Reaction	Literature	Fission of	with	Literature
$^2_1D + {}^4_2He = {}^1_1H + {}^1_0n + {}^4_2He$	S 23	Ionium	Neutrons	J 4
		Uranium	Protons of 6.9 MeV	D 18 b
		Thorium		D 18 b
$^2_1D + {}^1_1H = 2\,{}^1_1H + {}^1_0n$	B 6	Uranium	Deuterons	G 5, K 28, J 0
$^6_3Li + {}^2_1D = {}^3_2He + {}^4_2He + {}^1_0n$	R 34	Thorium	Deuterons, threshold value of about 7.5 MeV	K 28, J 0
		Uranium	α-particles of 32 MeV	F 14 a
$^7_3Li + {}^2_1D = 2\,{}^4_2He + {}^1_0n$	O 4, O 7, O 9, C 39, B 31, R 26, R 34	Uranium	γ-rays from $^{19}_9F + p$. Photodissociation	H 27, L 1a, H 27 b
$^9_4Be + {}^4_2He = 3\,{}^4_2He + {}^1_0n$	L 53	Thorium		H 27, H 27 b
$^9_4Be + e_\nu^- = {}^8_4Be + {}^1_0n + e_\nu^-$	C 26	$^{235}_{92}U$	Slow neutrons. $^{235}_{92}U$ is responsible for at least 75% of uranium fission with slow neutrons. $^{238}_{92}U$ cannot be disregarded completely but its contribution must be small.	N 16, N 17, K 14
$^{10}_5B + {}^2_1D = 3\,{}^4_2He$	C 19, C 22, C 23			
$^{10}_5B + {}^1_0n = 2\,{}^4_2He + {}^3_1H$	C 11, C 12			
$^{11}_5B + {}^1_1H = 3\,{}^4_2He$	C 17, C 18, O 3, K 16, D 12, L 1, Y 4, S 39			
$^{11}_5B + {}^2_1D = 3\,{}^4_2He + {}^1_0n$	C 23, B 34	$^{238}_{92}U$	Fast neutrons. $^{238}_{92}U$ gives fission only with fast neutrons and, indeed, is responsible for practically all uranium fissions by fast neutrons.	
$^{12}_6C + {}^1_0n = 3\,{}^4_2He + {}^1_0n$	C 9, A 32			
$^{14}_7N + {}^2_1D = 4\,{}^4_2He$	C 24			

Table VI

Reaction	Q (MeV)	Q (10^{-3} MU)	Literature
$^2_1D\ (d, p)\ {}^3_1H$	3.98 ± 0.02	4.27 ± 0.02	O 9 corrected by L 53
$^2_1D\ (d, n)\ {}^3_2He$	3.18 ± 0.13	3.42 ± 0.13	B 32 corrected by L 53
$^2_1D\ (d, n)\ {}^3_2He$	3.29 ± 0.08	3.53 ± 0.09	B 38
$^2_1D\ (d, n)\ {}^3_2He$	3.31 ± 0.03	3.56 ± 0.03	B 40 b
$^2_1D\ (\gamma, n)\ {}^1_1H$	— 2.189 ± 0.022	— 2.351 ± 0.024	S 52
$^2_1D\ (\gamma, n)\ {}^1_1H$	— 2.18 ± 0.07	— 2.34 ± 0.08	R 8

Table VI

Reaction	Q (MeV)	Q (10^{-3} MU)	Literature
$^{2}_{1}D$ (γ, n) $^{1}_{1}H$	-2.17 ± 0.05	-2.33 ± 0.05	R 21
$^{2}_{1}D$ (γ, n) $^{1}_{1}H$	-2.189 ± 0.007	-2.351 ± 0.008	K 11
$^{6}_{3}Li$ (p, α) $^{3}_{2}He$	3.72 ± 0.08	4.00 ± 0.09	N 8 corrected by L 53
$^{6}_{3}Li$ (p, α) $^{3}_{2}He$	$3.94_5 \pm 0.06$	4.24 ± 0.07	P 7
$^{6}_{3}Li$ (p, α) $^{3}_{2}He$	3.94 ± 0.08	4.23 ± 0.09	M 34 a, A 18 a
$^{6}_{3}Li$ (d, α) $^{4}_{2}He$	22.20 ± 0.04	23.84 ± 0.04	S 40
$^{6}_{3}Li$ (d, p) $^{7}_{3}Li$	5.02 ± 0.12	5.40 ± 0.13	C 19 corrected by L 53
$^{6}_{3}Li$ (n, α) $^{3}_{1}H$	4.67 ± 0.05	5.02 ± 0.05	L 52 corrected by L 53
$^{6}_{3}Li$ (n, α) $^{3}_{1}H$	4.86 ± 0.04	5.22 ± 0.04	L 54
$^{7}_{3}Li$ (p, α) $^{4}_{2}He$	17.28 ± 0.03	18.56 ± 0.03	S 40
$^{7}_{3}Li$ (p, n) $^{7}_{4}Be$	-1.62 ± 0.02	-1.74 ± 0.02	H 25, H 27 a
$^{7}_{3}Li$ (d, n) $^{8}_{4}Be$	14.55	15.63	B 31 corrected by L 53
$^{7}_{3}Li$ (d, α) $^{5}_{2}He$	12.7	13.6	W 19 corrected by F 18 a
$^{7}_{3}Li$ (d, p) $^{8}_{3}Li$	-0.200 ± 0.030	-0.21 ± 0.032	R 34
$^{8}_{4}Be \rightarrow 2\ ^{4}_{2}He$	< 0.20	< 0.21	L 1
$^{9}_{4}Be$ (p, α) $^{6}_{3}Li$	2.078 ± 0.04	2.232 ± 0.04	A 15 corrected by M 9 a
$^{9}_{4}Be$ (p, d) $^{8}_{4}Be$	0.534 ± 0.006	0.573 ± 0.006	A 16 corrected by M 9 a
$^{9}_{4}Be$ (p, n) $^{9}_{5}B$	-1.83 ± 0.01	-1.96 ± 0.01	H 26, H 27 a
$^{9}_{4}Be$ (d, n) $^{10}_{5}B$	4.20	4.51	B 34 corrected by L 53
$^{9}_{4}Be$ (d, α) $^{7}_{3}Li$	7.19 ± 0.12	7.72 ± 0.13	O 10 corrected by L 53
$^{9}_{4}Be$ (d, α) $^{7}_{3}Li$	7.093 ± 0.022	7.618 ± 0.024	G 17
$^{9}_{4}Be$ (d, p) $^{10}_{4}Be$	4.59 ± 0.11	4.93 ± 0.12	O 10 corrected by L 53
$^{9}_{4}Be$ (d, p) $^{10}_{4}Be$	4.52	4.85	P 20
$^{9}_{4}Be$ (γ, n) $^{8}_{4}Be$	-1.63 ± 0.05	-1.75 ± 0.05	C 26
$^{9}_{4}Be$ (γ, n) $^{8}_{4}Be$	-1.63 ± 0.05	-1.75 ± 0.05	C 26
$^{10}_{5}B$ (α, p) $^{13}_{6}C$	3.7	4.0	M 10
$^{10}_{5}B$ (p, n) $^{10}_{6}C$	-5.1	-5.5	B 7
$^{10}_{5}B$ (d, n) $^{11}_{6}C$	6.08	6.53	B 34 corrected by L 53
$^{10}_{5}B$ (d, α) $^{8}_{4}Be$	17.76 ± 0.08	19.10 ± 0.09	C 23 corrected by L 53
$^{10}_{5}B$ (d, p) $^{11}_{5}B$	9.14 ± 0.06	9.82 ± 0.06	C 23 corrected by L 53
$^{10}_{5}B$ (n, α) $^{7}_{3}Li$	2.75 ± 0.08	2.95 ± 0.09	L 54
$^{10}_{5}B$ (n, α) $^{7}_{3}Li$	2.90	3.11	M 11, F 16
$^{11}_{5}B$ (α, p) $^{14}_{6}C$	0.66 ± 0.30	0.71 ± 0.32	P 19
$^{11}_{5}B$ (p, α) $^{8}_{4}Be$	8.60 ± 0.11	9.24 ± 0.12	O 10 corrected by L 53
$^{11}_{5}B$ (p, n) $^{11}_{6}C$	-2.72 ± 0.01	-2.93 ± 0.01	H 26, H 27 a
$^{11}_{5}B$ (d, n) $^{12}_{6}C$	13.4	14.4	B 34 corrected by L 53
$^{11}_{5}B$ (d, α) $^{9}_{4}Be$	8.13 ± 0.12	8.73 ± 0.13	C 23 corrected by L 53
$^{12}_{6}C$ (d, n) $^{13}_{7}N$	-0.28	-0.30	C 24 corrected by L 53
$^{12}_{6}C$ (d, n) $^{13}_{7}N$	-0.25 ± 0.03	-0.27 ± 0.03	B 34 corrected by B 37
$^{12}_{6}C$ (d, n) $^{13}_{7}N$	-0.19 ± 0.05	-0.20 ± 0.05	B 18 a
$^{12}_{6}C$ (d, p) $^{13}_{6}C$	2.71 ± 0.05	2.91 ± 0.05	C 24 corrected by L 53
$^{12}_{6}C$ (p, n) $^{13}_{7}N$	-2.97 ± 0.03	-3.19 ± 0.03	H 25, H 27 a
$^{12}_{6}C$ (d, p) $^{14}_{6}C$	6.01 ± 0.20	6.46 ± 0.22 [1]	P 19
$^{12}_{6}C$ (d, p) $^{14}_{6}C$	6.1	6.55	B 54
$^{12}_{6}C$ (d, α) $^{10}_{5}B$	5.24 ± 0.11	5.63 ± 0.12	C 24 corrected by L 53
$^{14}_{7}N$ (α, p) $^{17}_{8}O$	-1.16	-1.25	P 14 corrected by L 53
$^{14}_{7}N$ (d, α) $^{12}_{6}C$	13.40 ± 0.15	14.40 ± 0.16	C 24 corrected by L 53
$^{14}_{7}N$ (d, α) $^{12}_{6}C$	13.39 ± 0.08	14.39 ± 0.09	H 63 a
$^{14}_{7}N$ (d, p) $^{15}_{7}N$	8.55 ± 0.08	9.18 ± 0.09	C 24 corrected by L 53
$^{14}_{7}N$ (d, p) $^{15}_{7}N$	8.51 ± 0.1	9.14 ± 0.1	H 63 a
$^{14}_{7}N$ (n, α) $^{11}_{5}B$	-0.43 ± 0.1	-0.46 ± 0.1	B 4
$^{14}_{7}N$ (n, p) $^{14}_{6}C$	0.55 ± 0.03	0.59 ± 0.03	H 66
$^{15}_{7}N$ (p, α) $^{12}_{6}C$	5.00 ± 0.15	5.37 ± 0.16	B 62
$^{15}_{7}N$ (d, α) $^{13}_{6}C$	7.54 ± 0.07	8.09 ± 0.08	H 63 a

[1]) Recalculated from the value for mass of $^{14}_{6}C$ given by P 19, since there seems to be a typographical error in the value of Q.

Table VI

Reaction	Q (MeV)	Q (10^{-3} MU)	Literature
$^{16}_{8}O$ (d, n) $^{17}_{9}F$	— 1.7	— 1.8	N 11 corrected by L 53
$^{16}_{8}O$ (d, α) $^{14}_{7}N$	3.13 ± 0.13	3.36 ± 0.14	C 24 corrected by L 53
$^{16}_{8}O$ (d, p) $^{17}_{8}O$	1.95 ± 0.06	2.10 ± 0.06	C 24 corrected by L 53
$^{18}_{8}O$ (p, α) $^{15}_{7}N$	3.96 ± 0.15	4.25 ± 0.16	B 65
$^{18}_{8}O$ (p, n) $^{18}_{9}F$	— 2.42 ± 0.04	— 2.60 ± 0.04	D 28
$^{19}_{9}F$ (α, p) $^{22}_{10}Ne$	1.58	1.70	C 5 corrected by L 53
$^{19}_{9}F$ (p, α) $^{16}_{8}O$	8.15 ± 0.12	8.75 ± 0.13	H 34 corrected by L 53
$^{19}_{9}F$ (p, α) $^{16}_{8}O$	7.95	8.54	B 63
$^{19}_{9}F$ (p, n) $^{19}_{10}Ne$	— 3.97	— 4.26	W 16
$^{19}_{9}F$ (d, n) $^{20}_{10}Ne$	10.80 ± 0.20	11.60 ± 0.22	B 39
$^{19}_{9}F$ (d, α) $^{17}_{8}O$	9.84	10.57	B 63
$^{19}_{9}F$ (d, p) $^{20}_{10}F$	4.3	4.6	B 54
$^{20}_{10}Ne$ (d, p) $^{21}_{10}Ne$	4.88	5.24	P 23
$^{23}_{11}Na$ (α, p) $^{26}_{12}Mg$	1.91	2.05	K 21 corrected by L 53
$^{23}_{11}Na$ (p, n) $^{23}_{12}Mg$	— 4.58 ± 0.3	— 4.93 ± 0.3	W 16
$^{23}_{11}Na$ (d, α) $^{21}_{10}Ne$	6.85 ± 0.20	7.36 ± 0.22	L 18 corrected by L 53
$^{23}_{11}Na$ (d, α) $^{21}_{10}Ne$	6.75 ± 0.1	7.25 ± 0.11	M 44
$^{23}_{11}Na$ (d, p) $^{24}_{11}Na$	4.92 ± 0.30	5.30 ± 0.32	L 18 corrected by L 53
$^{23}_{11}Na$ (d, p) $^{24}_{11}Na$	4.76	5.11	M 44
$^{24}_{12}Mg$ (α, p) $^{27}_{13}Al$	— 1.82	— 1.96	D 33 corrected by L 53
$^{25}_{12}Mg$ (α, p) $^{28}_{13}Al$	— 1.05	— 1.13	D 33 corrected by L 53
$^{27}_{13}Al$ (α, p) $^{30}_{14}Si$	2.26	2.43	D 33 corrected by L 53
$^{27}_{13}Al$ (p, n) $^{27}_{14}Si$	— 6.1	— 6.55	K 32
$^{27}_{13}Al$ (p, n) $^{27}_{14}Si$	— 5.8 ± 0.1	— 6.2 ± 0.1	M 13
$^{27}_{13}Al$ (d, α) $^{25}_{12}Mg$	6.46 ± 0.14	6.94 ± 0.15	M 20 corrected by L 53
$^{27}_{13}Al$ (d, p) $^{28}_{13}Al$	5.79 ± 0.3	6.22 ± 0.3	M 20 corrected by L 53
$^{28}_{14}Si$ (α, p) $^{31}_{15}P$	— 2.23	— 2.40	H 29 corrected by L 53
$^{31}_{15}P$ (α, p) $^{34}_{16}S$	0.31	0.33	M 12 corrected by L 53
$^{31}_{15}P$ (d, p) $^{32}_{15}P$	5.9 ± 0.3	6.3 ± 0.3	P 22
$^{32}_{16}S$ (d, p) $^{33}_{16}S$	6.62	7.11	S 39 a
$^{32}_{16}S$ (α, p) $^{35}_{17}Cl$	— 2.10	— 2.25	H 29 corrected by L 53
$^{35}_{17}Cl$ (d, p) $^{36}_{17}Cl$	6.9 ± 0.3	7.4 ± 0.3	P 22, S 32
$^{35}_{17}Cl$ (d, p) $^{36}_{17}Cl$	6.31	6.78	S 34 b
$^{35}_{17}Cl$ (d, α) $^{33}_{16}S$	9.1	9.8	S 34 b
$^{37}_{17}Cl$ (d, p) $^{38}_{17}Cl$	4.0 ± 0.3	4.3 ± 0.3	P 22, S 32
$^{37}_{17}Cl$ (d, p) $^{38}_{17}Cl$	4.02	4.31	S 34 b
$^{40}_{18}A$ (d, p) $^{41}_{18}A$	4.37	4.69	D 6
$^{39}_{19}K$ (α, p) $^{42}_{20}Ca$	— 0.89	— 0.96	P 13 corrected by L 53
$^{39}_{19}K$ (d, p) $^{40}_{19}K$	5.6 ± 0.3	6.0 ± 0.3	P 22
$^{40}_{20}Ca$ (α, p) $^{43}_{21}Sc$	— 4.27	— 4.59	P 14 corrected by L 53
$^{45}_{21}Sc$ (α, p) $^{48}_{22}Ti$	— 0.3 ± 0.5	— 0.3 ± 0.5	P 17
$^{45}_{21}Sc$ (d, p) $^{46}_{21}Sc$	6.78 ± 0.3	7.28 ± 0.3	D 5
$^{48}_{22}Ti$ (α, p) $^{51}_{23}V$	1.10 ± 0.5	1.18 ± 0.5	D 3
$^{51}_{23}V$ (d, p) $^{52}_{23}V$	7.80 ± 0.3	8.38 ± 0.3	D 5
$^{55}_{25}Mn$ (d, p) $^{56}_{25}Mn$	6.57 ± 0.3	7.06 ± 0.3	D 5
$^{59}_{27}Co$ (d, p) $^{60}_{27}Co$	5.78	6.21	D 7
$^{61}_{28}Ni$ (p, n) $^{61}_{29}Cu$	— 3.0	— 3.2	W 14
$^{64}_{28}Ni$ (p, n) $^{64}_{29}Cu$	— 2.5	— 2.7	W 14
$^{63}_{29}Cu$ (d, p) $^{64}_{29}Cu$	5.70 ± 0.3	6.12 ± 0.3 [1]	D 5
$^{65}_{29}Cu$ (d, p) $^{66}_{29}Cu$	6.35 ± 0.3	6.82 ± 0.3 [1]	D 5
$^{63}_{29}Cu$ (p, n) $^{63}_{30}Zn$	— 4.0	— 4.3	W 14
$^{68}_{30}Zn$ (p, n) $^{68}_{31}Ga$	— 3.5	— 3.8	D 28
$^{68}_{30}Zn$ (p, n) $^{69}_{31}Ga$	— 3.6	— 3.9	W 14
$^{70}_{30}Zn$ (p, n) $^{70}_{31}Ga$	— 1.6	— 1.7	W 14
$^{75}_{33}As$ (d, p) $^{76}_{33}As$	5.80	6.23	D 7

[1]) Assignment uncertain.

Literature
for Tables IV - VI

(1) Abelson, Ph.: Physic. Rev. **55** (1939) 418.
(2) Abelson, Ph.: Physic. Rev. **55** (1939) 424 (abs. 18).
(3) Abelson, Ph.: Physic. Rev. **55** (1939) 670.
(4) Abelson, Ph.: Physic. Rev. **55** (1939) 876.
(5) Abelson, Ph.: Physic. Rev. **56** (1939) 1.
(6) Alexeeva, K.: C. R. Acad. Sci. USSR. **17** (1937) 13.
(7) Alexeeva, K.: C. R. Acad. Sci. USSR. **18** (1938) 553.
(8) Alichanian, A. I., A. I. Alichanow & B. S. Dzelepow: Physikal. Z. USSR. **10** (1936) 78.
(9) Alichanow, A. I., A. I. Alichanian & B. S. Dzelepow: Nature, London **133** (1934) 871.
(10) Alichanow, A. I., A. I. Alichanian & B. S. Dzelepow: Nature, London **134** (1934) 254.
(11) Alichanow, A. I., A. I. Alichanian & B. S. Dzelepow: Nature, London **135** (1935) 393.
(12) Alichanow, A. I., A. I. Alichanian & B. S. Dzelepow: Nature, London **136** (1935) 257.
(13) Allen, I. S.: Physic. Rev. **51** (1937) 182.
(14) Allison, S. K.: Physic. Rev. **49** (1936) 420. Proc. Cambridge phil. Soc. **32** (1936) 179.
(15) Allison, S. K., L. S. Skaggs & N. M. Smith jr.: Physic. Rev. **54** (1938) 171; & L. S. Skaggs: Physic. Rev. **56** (1939) 24.
(16) Allison, S. K., E. R. Graves, L. S. Skaggs & N. M. Smith jr.: Physic. Rev. **55** (1939) 107; & L. S. Skaggs: Physic. Rev. **56** (1939) 24.
(17) Allison, S. K., E. R. Graves & L. S. Skaggs: Physic. Rev. **57** (1940) 158.
(18) Allison, S. K., L. C. Miller, G. J. Perlow, L. S. Skaggs & N. M. Smith jr.: Physic. Rev. **58** (1940) 178.
(18a) Allison, S. K., L. C. Miller, L. S. Skaggs & N. M. Smith, jr.: Physic. Rev. **59** (1941) 108 (abs. 14).
(19) Alvarez, L. W.: Physic. Rev. **52** (1937) 134.
(20) Alvarez: L. W.: Physic. Rev. **53** (1938) 606.
(21) Alvarez, L. W.: Physic. Rev. **54** (1938) 486.
(22) Alvarez, L. W. & R. Cornog: Physic. Rev. **56** (1939) 379, 613; **57** (1940) 248.
(23) Alvarez, L. W., A. C. Helmholz & E. Nelson: Physic. Rev. **57** (1940) 660.
(24) Alvarez, L. W. & R. Cornog: Physic. Rev. **58** (1940) 197 (abs. 47).
(25) Amaki, T. & A. Sugimoto: Sci. Pap. Inst. physic. chem. Res. Japan **34** (1938) 1650.
(26) Amaki, T., T. Iiomori & A. Sugimoto: Sci. Pap. Inst. physic. chem. Res. Japan **37** (1940) 395. Physic. Rev. **57** (1940) 751.
(27) Amaldi, E., O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti & E. Segré: Proc. roy. Soc. London (A) **149** (1935) 522.
(28) Amaldi, E.: Nuovo Cim. **12** (1935) 235.
(29) Andersen, E. B.: Nature, London **137** (1936) 457.
(30) Andersen, E. B.: Z. physik. Chem. B **32** (1936) 237.
(31) Andersen, E. B.: Nature, London **138** (1936) 76.
(31a) Anderson, H. L., E. Fermi & A. V. Grosse: Physic. Rev. **59** (1941) 52.
(32) Aoki, A.: Proc. physic.-math. Soc. Japan **20** (1938) 755.
(33) Aten, A. H. W. jr., C. J. Bakker & F. A. Heyn: Nature, London **143** (1939) 679.

(1) Bacon, R. H., E. N. Grisewood & C. W. van der Merwe: Physic. Rev. **52** (1937) 668.
(2) Bacon, R. H., E. N. Grisewood & C. W. van der Merwe: Physic. Rev. **54** (1938) 315 (abs. 18).
(2a) Bacon, R. H., E. N. Grisewood & C. W. van der Merwe: Physic. Rev. **59** (1941) 531.
(3) Bak, M. A. & N. N. Nikolaevskaya: C. R. Acad. Sci. URSS. **22** (1939) 312.
(4) Baldinger, E. & P. Huber: Helv. physic. Acta **12** (1939) 330.
(5) Barkas, W. H.: Physic. Rev. **56** (1939) 287.
(6) Barkas, W. H. & M. G. White: Physic. Rev. **56** (1939) 288.
(7) Barkas, W. H., E. C. Creutz, L. A. Delsasso, J. G. Fox & M. G. White: Physic. Rev. **57** (1940) 562 (abs. 37).
(8) Barkas, W. H., E. C. Creutz, L. A. Delsasso & R. A. Sutton Physic. Rev. **57** (1940) 1087 (abs. 164).
(9) Barkas, W. H., E. C. Creutz, L. A. Delsasso, R. B. Sutton & M. G. White: Physic. Rev. **58** (1940) 194 (abs. 34), 383.
(10) Barkas, W. H., P. R. Carlson, J. E. Henderson & W. H. Moore: Physic. Rev. **58** (1940) 577.
(11) Barnes, S. W. & G. E. Valley: Physic. Rev. **53** (1938) 946.
(12) Barnes, S. W. & P. W. Aradine: Physic. Rev. **55** (1939) 50.
(13) Barnes, S. W.: Physic. Rev. **55** (1939) 241 (abs. 42); **56** (1939) 414, 859 (abs. 55).
(14) Barresi, G. & Cacciapuoti: Scientia **10** (1939) 464.
(15) Bayley, D. S. & H. R. Crane: Physic. Rev. **52** (1937) 604.
(16) Becker, R. A. & E. R. Gaerttner: Physic. Rev. **56** (1939) 854 (abs. 29).
(16a) Becker, R. A., W. A. Fowler & C. C. Lauritsen: Physic. Rev. **59** (1941) 217 (abs. 9).
(17) Bennett, W. E. & T. W. Bonner: Physic. Rev. **57** (1940) 1086 (abs. 160); **58** (1940) 183.
(18) Bennett, W. E., T. W. Bonner, E. Hudspeth & B. E. Watt: Physic. Rev. **58** (1940) 478.
(18a) Bennett, W. E., T. W. Bonner, E. Hudspeth, H. T. Richards & B. E. Watt: Physic. Rev. **59** (1941) 781.
(18b) Bennett, W. E., T. W. Bonner & B. E. Watt: Physic. Rev. **59** (1941) 793.
(18c) Bennett, W. E., T. W. Bonner, H. T. Richards & B. E. Watt: Physic. Rev. **59** (1941) 904.
(19) Bernardini, G.: Scientia **8** (1937) 33.
(20) Bernardini, G.: Nuovo Cim. **15** (1938) 220.
(21) Bertl, E., F. Obořil & K. Sitte: Z. Physik **106** (1937) 463.
(22) Bethe, H. A. & W. J. Henderson: Physic. Rev. **56** (1939) 1060.
(23) Bjerge, T. & C. H. Westcott: Nature, London **134** (1934) 177.
(24) Bjerge, T. & C. H. Westcott: Nature, London **134** (1934) 286.
(25) Bjerge, T.: Nature, London **137** (1936) 865.
(26) Bjerge, T.: Nature, London **138** (1936) 400.
(27) Bjerge, T. & K. J. Broström: Nature, London **138** (1936) 400.
(28) Bjerge, T.: Nature, London **139** (1937) 757.
(29) Bjerge, T. & K. J. Broström: Det. Kgl. Danske Vid. Selskab. **16** (1938) 17.
(30) Bonner, T. W. & L. M. Mott-Smith: Physic. Rev. **46** (1934) 258.
(31) Bonner, T. W. & W. M. Brubaker: Physic. Rev. **48** (1935) 742.

(32) Bonner, T. W. & W. M. Brubaker: Physic. Rev. **49** (1936) 19.
(33) Bonner, T. W. & W. M. Brubaker: Physic. Rev. **49** (1936) 778.
(34) Bonner, T. W. & W. M. Brubaker: Physic. Rev. **50** (1936) 308.
(35) Bonner, T. W. & W. M. Brubaker: Physic. Rev. **50** (1936) 308.
(36) Bonner, T. W.: Physic. Rev. **52** (1937) 685.
(37) Bonner, T. W.: Physic. Rev. **53** (1938) 496.
(38) Bonner, T. W.: Physic. Rev. **53** (1938) 711.
(39) Bonner, T. W.: Proc. roy. Soc. London (A) **174** (1940) 339.
(40) Bonner, T. W., E. Hudspeth & W. E. Bennett: Physic. Rev. **57** (1940) 1075 (abs. 103); **58** (1940) 185.
(40a) Bonner, T. W., R. A. Becker, S. Rubin & J. F. Streib: Physic. Rev. **59** (1941) 215 (abs. 3).
(40b) Bonner, T. W.: Physic. Rev. **59** (1941) 237.
(41) Booth, E. T. & C. Hurst: Proc. roy. Soc. London (A) **161** (1937) 248.
(42) Booth, E. T., J. R. Dunning, A. V. Grosse & A. O. Nier: Physic. Rev. **58** (1940) 475.
(43) Borst, L. B. & W. D. Harkins: Physic. Rev. **57** (1940) 569.
(43a) Borst, L. B.: Physic. Rev. **59** (1941) 941 (abs. 141).
(44) Bothe, W. & H. Becker: Z. Physik **66** (1930) (289).
(45) Bothe, W. & H. Fränz: Z. Physik **43** (1927) 456; **49** (1928) 1; **63** (1930) 370, 381.
(46) Bothe, W. & W. Gentner: Naturwiss. **25** (1937) 90.
(47) Bothe, W. & W. Gentner: Naturwiss. **25** (1937) 126.
(48) Bothe, W. & W. Gentner: Naturwiss. **25** (1937) 191.
(49) Bothe, W. & W. Gentner: Naturwiss. **25** (1937) 284.
(50) Bothe, W. & H. Maier-Leibnitz: Z. Physik **107** (1937) 513.
(51) Bothe, W. & W. Gentner: Z. Physik **106** (1937) 236.
(52) Bothe, W. & W. Gentner: Naturwiss. **26** (1938) 497.
(53) Bothe, W. & W. Gentner: Z. Physik **112** (1939) 45.
(54) Bower, J. C. & W. E. Burcham: Proc. roy. Soc. London (A) **173** (1939) 379.
(55) Bramley, A. & A. K. Brewer: Physic. Rev. **53** (1938) 502.
(56) Brandt, H.: Z. Physik **108** (1938) 276.
(57) Brasch, A.: Naturwiss. **21** (1933) 82.
(58) Brasefield, C. J. & E. Pollard: Physic. Rev. **50** (1936) 296.
(58a) Bretscher, E.: Nature (Lond.) **146** (1940) 94.
(58b) Bretscher, E. & L. G. Cook: Nature, London **146** (1940) 430.
(59) Brown, M. V. & C. G. Mitchell: Physic. Rev. **50** (1936) 593.
(59a) Brown, S. C.: Physic. Rev. **59** (1941) 687 (abs. 23).
(60) Brubaker, W. M. & E. Pollard: Physic. Rev. **51** (1937) 1013.
(61) Buck, J. H.: Physic. Rev. **54** (1938) 1025.
(62) Burcham, W. E. & M. Goldhaber: Proc. Cambridge phil. Soc. **32** (1936) 632.
(63) Burcham, W. E. & C. L. Smith: Proc. roy. Soc. London (A) **168** (1938) 176.
(64) Burcham, W. E., M. Goldhaber & R. D. Hill: Nature, London **141** (1938) 510.
(65) Burcham, W. E. & C. L. Smith: Nature, London **143** (1939) 795.
(66) Burcham, W. E. & S. Devons: Proc. roy. Soc. London (A) **173** (1939) 555.

(1) Cacciapuoti, B. N. & E. Segrè: Physic. Rev. **52** (1937) 1252.
(2) Cacciapuoti, B. N.: Nuovo Cim. **15** (1938) 425. Physic. Rev. **55** (1939) 110.
(3) Cacciapuoti, N. B.: Nuovo Cim. **15** (1938) 213.
(4) Carlson, P. R. & J. E. Henderson: Physic. Rev. **58** (1940) 193 (abs. 28).
(5) Chadwick, J. & J. E. R. Constable: Proc. roy. Soc. London (A) **135** (1931) 48.
(6) Chadwick, J.: Proc. roy. Soc. London **136** (1932) 692.
(7) Chadwick, J.: Proc. roy. Soc. London (A) **142** (1933) 1.
(8) Chadwick, J. & N. Feather: Int. Conf. Phys: London 1934.
(9) Chadwick, J., N. Feather & W. T. Davies: Proc. Cambridge phil. Soc. **30** (1934) 357.
(10) Chadwick, J. & M. Goldhaber: Proc. roy. Soc. London (A) **151** (1935) 479.
(11) Chadwick, J. & M. Goldhaber: Nature, London **135** (1935) 65.
(12) Chadwick, J. & M. Goldhaber: Proc. Cambridge phil. Soc. **31** (1935) 612.
(13) Chang, W. V., M. Goldhaber & R. Sagane: Nature, London **139** (1937) 962.
(14) Chang, W. V. & A. Szalay: Proc. roy. Soc. London (A) **159** (1937) 72.
(15) Cichocki, J. & A. Soltan: C. R. Séances Acad. Sci. Paris **207** (1938) 423.
(16) Clancy, E. P.: Physic. Rev. **58** (1940) 88.
(16a) Clancy, E. P.: Physic. Rev. **59** (1941) 686 (abs. 21).
(17) Cockroft, J. D. & E T. Walton: Proc. roy. Soc. London (A) **137** (1932) 229. Nature, London **129** (1932) 242, 649.
(18) Cockroft, J. D. & E. T. Walton: Nature London **131** (1933) 23.
(19) Cockroft, J. D. & E. T. Walton: Proc. roy. Soc. London (A) **144** (1934) 704.
(20) Cockroft, J. D.: Int. Conf. Phys. London 1934.
(21) Cockroft, J. D., C. W. Gilbert & E. T. S. Walton: Nature **133** (1934) 328.
(22) Cockroft, J. D., C. W. Gilbert & E. T. S. Walton: Proc. roy. Soc. London (A) **148** (1935) 225.
(23) Cockroft, J. D. & W. B. Lewis: Proc. roy. Soc. London (A) **154** (1936) 246.
(24) Cockroft, J. D. & W. B. Lewis: Proc. roy. Soc. London (A) **154** (1936) 261.
(24a) Collar, H. W., J. M. Cork & G. P. Smith: Physic. Rev. **59** (1941) 937 (abs. 120).
(25) Collins, G. B., B Waldman, E. M. Stubblefield & M. Goldhaber: Physic. Rev. **55** (1939) 507.
(26) Collins, G. B., B. Waldman & E. Guth: Physic. Rev. **56** (1939) 876.
(27) Collins, G. B. & B. Waldman: Physic. Rev. **57** (1940) 1088 (abs. 169).
(27a) Collins, G. B. & B. Waldman: Physic. Rev. **59** (1941) 109 (abs. 20).
(27b) Cooper, E. P. & E. C. Nelson: Physic. Rev. **58** (1940) 1117.
(28) Cork, J. M., J. R. Richardson & F. N. Kurie: Physic. Rev. **49** (1936) 208.
(29) Cork, J. M. & E. O. Lawrence: Physic. Rev. **49** (1936) 788 (abs. 28).
(30) Cork, J. M. & R. L. Thornton: Physic. Rev. **51** (1937) 59 (abs. 9).

(31) Cork, J. M. & R. L. Thornton: Physic. Rev. **51** (1937) 608.
(32) Cork, J. M. & R. L. Thornton: Physic. Rev. **53** (1938) 866.
(33) Cork, J. M. & J. L. Lawson: Pysik. Rev. **56** (1939) 291.
(34) Cork, J. M., J. Halpern & H. Tatel: Physic. Rev. **57** (1940) 348, 371 (abs. 20).
(35) Cork, J. M. & J. Halpern: Physic. Rev. **58** (1940) 201 (abs. 13).
(36) Cork, J. M. & W. Middleton: Physic. Rev. **58** (1940) 474.
(37) Corson, D. R., K. R. MacKenzie & E. Segrè: Physic. Rev. **57** (1940) 250, 459, 1087 (abs. 165).
(37a) Corson, D. R., K. R. MacKenzie & E. Segrè: Physic. Rev. **58** (1940) 672.
(38) Crane, H. R., C. C. Lauritsen & A. Soltan: Physic. Rev. **44** (1933) 514.
(39) Crane, H. R., C. C. Lauritsen & A. Soltan: Physic. Rev. **44** (1933) 692.
(40) Crane, H. R. & C. C. Lauritsen: Physic. Rev. **45** (1934) 430.
(41) Crane, H. R. & C. C. Lauritsen: Physic. Rev. **45** (1934) 497.
(42) Crane, H. R., L. A. Delsasso, W. H. Fowler & C. C. Lauritsen: Physic. Rev. **46** (1934) 1109.
(43) Crane, H. R., L. A. Delsasso, W. A. Fowler & C. C. Lauritsen: Physic. Rev. **47** (1925) 782.
(44) Crane, H. R., L. A. Delsasso, W. A. Fowler & C. C. Lauritsen: Physic. Rev. **47** (1935) 887.
(45) Crane, H. R., L. A. Delsasso, W. A. Fowler & C. C. Lauritsen: Physic. Rev. **47** (1935) 971.
(46) Crane, H. R., L. A. Delsasso, W. A. Fowler & C. C. Lauritsen: Physic. Rev. **48** (1935) 102.
(47) Crane, H. R., L. A. Delsasso, W. A. Fowler & C. C. Lauritsen: Physic. Rev. **48** (1935) 484.
(48) Creutz, E. C., J. G. Fox & R. Sutton: Physic. Rev. **57** (1940) 567 (abs. 60).
(49) Creutz, E. C., L. A. Delsasso, R. B. Sutton, M. G. White & W. H. Barkas: Physic. Rev. **58** (1940) 481.
(49a) Creutz, E. C., W. H. Barkas & N. H. Furman: Physic. Rev. **58** (1940) 1008.
(50) Crittenden, E. C. jr. & R. F. Bacher: Physic. Rev. **54** (1938) 862.
(51) Crittenden, E. C. jr.: Physic. Rev. **56** (1939) 709.
(52) Curie, I. & F. Joliot: J. Physiq. Radium **4** (1933) 21.
(53) Curie, I. & F. Joliot: C. R. Séances Acad. Sci. Paris **197** (1933) 237.
(54) Curie, I. & F. Joliot: J. Physiq. Radium **4** (1933) 278.
(55) Curie, I. & F. Joliot: C. R. Séances Acad. Sci. Paris **198** (1934) 254.
(56) Curie, M. & P. Preiswerk: C. R. Séances Acad. Sci. Paris **203** (1934) 787.
(57) Curran, S. C., P. I. Dee & V. Petržilka: Proc. roy. Soc. London (A) **169** (1938) 269.
(58) Curran, S. C. & J. E. Strothers: Proc. roy. Soc. London (A) **172** (1939) 72.
(59) Curran, S. C. & J. E. Strothers: Nature, London **145** (1940) 224.
(60) Curran, S. C., P. I. Dee & J. E. Strothers: Proc. roy. Soc. London (A) **174** (1940) 546.
(61) Curran, S. C. & J. E. Strothers: Proc. Cambridge phil. Soc. **36** (1940) 252.
(62) Curtis, B. R. & J. M. Cork: Physic. Rev. **53** (1938) 681 (abs. 33).
(63) Curtis, B. R. & J. R. Richardson: Physic. Rev. **53** (1938) 942 (abs. 145); **57** (1940) 1121.
(64) Curtis, B. R.: Physic. Rev. **55** (1939) 1136.
(1) Danysz, M. & M. Zyw: Acta physic. Pol. **3** (1934) 485.
(2) Darling, B. T., B. R. Curtis & J. M. Cork: Physic. Rev. **51** (1937) 1010 (abs. 67).
(3) Davidson, W. L. jr. & E. Pollard: Physic. Rev. **54** (1938) 408.
(4) Davidson, W. L. jr.: Physic. Rev. **56** (1939) 1061.
(5) Davidson, W. L. jr.: Physic. Rev. **56** (1939) 1062.
(6) Davidson, W. L. jr: Physic. Rev. **57** (1940) 244.
(7) Davidson, W. L. jr.: Physic. Rev. **57** (1940) 568 (abs. 63).
(8) Davidson, W. L. jr.: Physic. Rev. **57** (1940) 1086 (abs. 161).
(9) Dee, P. I. & E. T. S. Walton: Proc. roy. Soc. London (A) **141** (1933) 733.
(10) Dee, P. I.: Proc. roy. Soc. London **148** (1935) 623.
(11) Dee, P. I. & C. W. Gilbert: Proc. roy. Soc. London (A) **149** (1935) 200.
(12) Dee, P. I. & C. W. Gilbert: Proc. roy. Soc. London (A) **154** (1936) 279.
(13) Dee, P. I., S. C. Curran & V. Petržilka: Nature, London **141** (1938) 642.
(14) Dee, P. I., S. C. Curran & J. E. Strothers: Nature, London **143** (1939) 759.
(15) Delsasso, L. A., W. A. Fowler & C. C. Lauritsen: Physic. Rev. **48** (1935) 848.
(16) Delsasso, L. A., W. A. Fowler & C. C. Lauritsen: Physic. Rev. **51** (1937) 391.
(17) Delsasso, L. A., W. A. Fowler & C. C. Lauritsen: Physic. Rev. **51** (1937) 527.
(18) Delsasso, L. A., L. N. Ridenour, R. Sheer & M. G. White: Physic. Rev. **55** (1939) 113.
(18a) Delsasso, L. A., M. G. White, W. Barkas & E. C. Creutz: Physic. Rev. **58** (1940) 586.
(18b) Dessauer, G. & E. M. Hafner: Physic. Rev. **59** (1941) 840, 940 (abs. 139).
(18c) Deutsch, M.: Physic. Rev. **59** (1941) 684 (abs. 12).
(18d) Deutsch, M.: Physic. Rev. **59** (1941) 940 (abs. 137).
(19) De Vault, D. C. & W. F. Libby: Physic. Rev. **55** (1939) 322.
(20) Dickson, G., P. W. McDaniel & E. J. Konopinski: Physic. Rev. **57** (1940) 351.
(21) Diebner, K. & H. Pose: Z. Physik **75** (1932) 753.
(22) Dodé, M. & B. Pontecorvo: C. R. Séances Acad. Sci. Paris **207** (1938) 287.
(23) Dodson, R. W. & R. D. Fowler: Physic. Rev. **55** (1939) 880.
(24) Dodson, R. W. & R. D. Fowler: Physic. Rev. **57** (1940) 967.
(25) Döpel, R.: Z. Physik **91** (1934) 796.
(26) Döpel, R.: Physikal. Z. **37** (1936) 96.
(27) Döpel, R.: Z. Physik **104** (1937) 671.
(27a) Downing, J. R. & A. Roberts: Physic. Rev. **59** (1941) 940 (abs. 138).
(28) Du Bridge, L. A., S. W. Barnes, J. H. Buck & C. V. Strain: Physic. Rev. **53** (1938) 447.
(29) Du Bridge, L. A.: Physic. Rev. **55** (1939) 603 (abs. 32).
(30) Du Bridge, L. A. & J. Marshall: Physic. Rev. **56** (1939) 706.
(31) Du Bridge, L. A. & T. Marshall: Physic. Rev. **57** (1940) 348 (abs. 19); **58** (1940) 7.
(32) Du Bridge, L. A. & Co-workers: Priv. comm. to J. J. Livingood & G. T. Seaborg. Rev. mod. Physics **12** (1940) 30 & G. T. Seaborg: Chem. Rev. **27** (1940) 199.

(33) Duncanson, W. E. & H. Miller: Proc. roy. Soc. London (A) **146** (1934) 396.
(34) Dunning, J. R.: Physic. Rev. **45** (1934) 586.
(35) Dunning, J. R., G. B. Fink & D. P. Mitchell: Physic. Rev. **48** (1935) 265.
(36) Dunworth, J. V.: Nature, London **144** (1939) 152.
(37) Dunworth, J. V.: Nature, London **143** (1939) 1065.

(1) Eckard, A.: Ann. Physik **29** (1937) 497.
(2) Ellet, A., W. B. McLean, V. J. Young, G. T. Plain: Physic. Rev. **57** (1940) 1083 (abs. 143).
(2a) Elliott, D. R. & L. D. P. King: Physic. Rev. **59** (1941) 403.
(3) Ellis, C. D. & W. J. Henderson: Nature, London **135** (1935) 429.
(4) Ellis, C. D. & W. J. Henderson: Proc. roy. Soc. London (A) **156** (1936) 358.
(5) Enns, T.: Physic. Rev. **56** (1939) 872.
(6) Erbacher, O. & K. Philipp: Angew. Chem. **48** (1935) 409.
(7) Erbacher, O. & K. Philipp: Z. physik. Chem. A **176** (1936) 169.
(8) Erbacher, O. & K. Philipp: Ber. Deutsch. chem. Ges. **69** (1936) 893.
(9) Erbacher, O. & K. Philipp: Z. physik. Chem. A **179** (1937) 263.
(10) Erbacher, O.: Z. physik. Chem. B **42** (1939) 173.
(11) Ewing, D., T. Perry & R. L. McCreary: Physic. Rev. **55** (1939) 1136 (abs. 130).
(12) Ewing, D.: Priv. comm. to J. J. Livingood & G. F. Seaborg. Rev. mod. Physic. **12** (1940) 30.

(1) Fahlenbrach, H.: Z. Physik **94** (1935) 607.
(2) Fahlenbrach, H.: Z. Physik **96** (1935) 503.
(3) Fajans, K. & D. W. Stuart: Physic. Rev. **56** (1939) 625.
(4) Fajans, K. & A. F. Voigt: Physic. Rev. **58** (1940) 177.
(5) Fajans, K. & W. H. Sullivan: Physic. Rev. **58** (1940) 276.
(6) Fay, J. W. J. & F. A. Paneth: J. chem. Soc. London **1936**, 384.
(7) Feather, N.: Proc. roy. Soc. London (A) **136** (1932) 709.
(8) Feather, N.: Nature, London **130** (1932) 257.
(9) Feather, N.: Proc. roy. Soc. London (A) **142** (1933) 689.
(10) Feather, N. & E. Bretscher: Proc. roy. Soc. London (A) **165** (1938) 530.
(11) Feather, N. & J. V. Dunworth: Proc. Cambridge phil. Soc. **34** (1938) 442.
(12) Feather, N. & J. V. Dunworth: Proc. roy. Soc. London (A) **168** (1938) 566.
(13) Feather, N. & E. Bretscher: Nature, London **143** (1939) 516.
(13a) Feldmeier, J. R. & G. B. Collins: Physic. Rev. **59** (1941) 937 (abs. 123).
(14) Fermi, E., E. Amaldi, O. D'Agostino, F. Rasetti & E. Segrè: Proc. roy. Soc. London (A) **146** (1934) 483.
(14a) Fermi, A. & E. Segrè: Physic. Rev. **59** (1941) 680.
(15) Fischer-Colbrie, E.: Akad. Wiss. Wien **145** (1936) 283.
(16) Fisk, J. B.: Physic. Rev. **55** (1939) 1117 (abs. 35).
(17) Flammersfeld, A.: Z. Physik **112** (1939) 727.
(18) Fleischmann, R.: Z. Physik **103** (1936) 113.
(18a) Flügge, S. & J. Mattauch: Physikal. Z. **42** (1941) 1.
(19) Fomin, V. & F. G. Houtermans: Physikal. Z. USSR. **9** (1936) 273.
(20) Fowler, W. A., L. A. Delsasso & C. C. Lauritsen: Physic. Rev. **49** (1936) 561.
(21) Fowler, W. A. & C. C. Lauritsen: Physic. Rev. **56** (1939) 840.
(22) Fowler, W. A. & C. C. Lauritsen: Physic. Rev. **58** (1940) 192 (abs. 26).
(23) Fox, J. G., E. G. Creutz, M. G. White & L. A. Delsasso: Physic. Rev. **55** (1939) 1106.
(24) Friedlaender: Priv. commun. to J. J. Livingood & G. T. Seaborg. Rev. mod. Physic. **12** (1940) 30.
(25) Frisch, O. R.: Nature, London **133** (1934) 721.
(26) Frisch, O. R.: Nature, London **136** (1935) 220.
(27) Fünfer, E.: Ann. Physik **29** (1937) 1.

(1) Gadsinski, N. N., I. A. Golotzwan & A. I. Danilenko: J. exper. theor. Physik **10** (1940) 1.
(2) Gaerttner, E. R., J. J. Turin & H. R. Crane: Physic. Rev. **49** (1936) 793.
(3) Gaerttner, E. R. & H. R. Crane: Physic. Rev. **51** (1937) 49.
(4) Gaerttner, E. R. & L. A. Pardue: Physic. Rev. **57** (1940) 386.
(5) Gant, D. H. T.: Nature, London **144** (1939) 707.
(5a) Geiger, H.: Z. Physik **8** (1922) 45.
(6) Gentner, W.: Z. Physik **107** (1937) 354.
(7) Gentner, W.: Naturwiss. **26** (1938) 109.
(8) Gentner, W. & E. Segré: Physic. Rev. **55** (1939) 814.
(9) Giarratana, J. & C. G. Brennecke: Physic. Rev. **49** (1936) 35.
(10) Glasoe, G. N. & J. Steigman: Physic. Rev. **57** (1940) 566; **58** (1940) 1.
(11) Glückauf, E. & F. A. Paneth: Proc. roy. Soc. London (A) **165** (1938) 229.
(12) Götte, H.: Naturwiss. **28** (1940) 449.
(12a) Götte, H.: Naturw. **29** (1941) 496.
(12b) Götte, H. & W. Seelmann-Eggebert: Private communication.
(13) Goldhaber, M., R. D. Hill & L. Szillard: Physic. Rev. **55** (1939) 47. Nature, London **142** (1938) 521.
(13a) Goldhaber M.: Nature, London **146** (1940) 167.
(14) Govaerts, J.: Nature, London **145** (1940) 624.
(15) Grahame, D. C. & G. T. Seaborg: Physic. Rev. **54** (1938) 240 (abs. 28).
(16) Grahame, D. C. & H. Walke: Priv. comm. to J. J. Livingood & G. T. Seaborg. Rev. mod. Physic. **12** (1940) 30.
(17) Graves, E. R.: Physic. Rev. **57** (1940) 855.
(18) Grinberg, A. P. & L. I. Roussinow: Physic. Rev. **58** (1940) 181.
(19) Grosse, A. V., E. T. Booth & J. R. Dunning: Physic. Rev. **56** (1939) 382.
(20) Grosse, A. V. & E. T. Booth: Physic. Rev. **57** (1940) 664.
(20a) Grosse, A. V., E. T. Booth & J. R. Dunning: Physic. Rev. **59** (1941) 322.
(21) Guében, G.: Nature, London **138** (1936) 1095.
(22) Guében, G. & S. A. Bull: Soc. roy. Liége **7** (1938) 565.

(1) Hafstad, L. R. & M. A. Tuve: Physic. Rev. **48** (1935) 306.
(2) Hafstad, L. R., N. P. Heydenburg & M. A. Tuve: Physic. Rev. **49** (1936) 866.
(2a) Haggstrom, E.: Physic. Rev. **59** (1941) 322.
(3) Hahn, O.: Ber. Deutsch. chem. Ges. **54** (1921) 1131. Z. physik. Chem. **103** (1923) 461.
(4) Hahn, O. & L. Meitner: Naturwiss. **23** (1935) 320.

(5) Hahn, O. & L. Meitner: Naturwiss. **24** (1936) 158.
(6) Hahn, O., F. Strassmann & E. Walling: Naturwiss. **25** (1937) 189.
(7) Hahn, O. & F. Strassmann: Naturwiss. **27** (1939) 11.
(8) Hahn, O. & F. Strassmann: Naturwiss. **27** (1939) 89.
(9) Hahn, O. & F. Strassmann: Naturwiss. **27** (1939) 163.
(10) Hahn, O. & F. Strassmann: Naturwiss. **27** (1939) 451.
(11) Hahn, O. & F. Strassmann: Naturwiss. **27** (1939) 529.
(12) Hahn, O., F. Strassmann & S. Flügge: Naturwiss. **27** (1939) 544.
(13) Hahn, O. & F. Strassmann: Physikal. Z. **40** (1939) 673.
(14) Hahn, O. & F. Strassmann: Abh. Preuß. Akad. Wiss. **1939**, Nr. 12.
(15) Hahn, O. & F. Strassmann: Naturwiss. **28** (1940) 54.
(16) Hahn, O. & F. Strassmann: Naturwiss. **28** (1940) 61.
(17) Hahn, O., S. Flügge & J. Mattauch: Physikal. Z. **41** (1940) 1.
(18) Hahn, O. & F. Strassmann: Naturwiss. **28** (1940) 543.
(19) Hahn, O. & F. Strassmann: Naturwiss. **28** (1940) 455.
(19a) Hahn, O. & F. Strassmann: Naturw. **28** (1940) 817.
(19b) Hahn, O. & F. Strassmann: Naturw. **29** (1941) 285.
(19c) Hahn, O. & F. Strassmann: Naturw. **29** (1941) 369.
(19d) Hahn, O. & F. Strassmann: Private communcation.
(20) Halpern, J. & H. R. Crane: Physic. Rev. **55** (1939) 260.
(21) Hancock, J. O. & J. C. Butler: Physic. Rev. **57** (1940) 1088 (abs. 168).
(21a) Hansen, W.: Physic. Rev. **59** (1941) 941 (abs. 144).
(22) Harkins, W. D., D. M. Gans & H. W. Newson: Physic. Rev. **44** (1935) 529.
(23) Harkins, W. D., D. M. Gans & H. W. Newson: Physic. Rev. **47** (1935) 52.
(24) Harteck, P., F. Knauer & W. Schaeffer: Naturwiss. **29** (1937) 477. Z. Physik **109** (1938) 153.
(25) Haxby, R. O., W. E. Shoupp, W. E. Stephens & W. H. Wells: Physic. Rev. **57** (1940) 348 (abs. 18).
(26) Haxby, R. O., W. E. Shoupp, W. E. Stephens & W. H. Wells: Physic. Rev. **57** (1940) 567 (abs. 58).
(27) Haxby, R. O., W. E. Shoupp, W. E. Stephens & W. H. Wells: Physic. Rev. **58** (1940) 92.
(27a) Haxby, R. O., W. E. Shoupp, W. E. Stephens & W. H. Wells: Physic. Rev. **58** (1940) 1035.
(27b) Haxby, R. O., W. E. Shoupp, W. E. Stephens & W. H. Wells: Physic. Rev. **59** (1941) 57.
(28) Haxel, O.: Z. Physik **83** (1933) 323.
(29) Haxel, O.: Physikal. Z. **36** (1935) 840.
(30) Haxel, O.: Z. Physik **93** (1935) 400.
(31) Haxel, O.: Z. Physik **104** (1937) 540.
(31a) Helmholtz, A. C.: Private commun. to G. T. Seaborg: Chem. Rev. **27** (1940) 199.
(31b) Helmholtz, A. C., C. Pecher & P. R. Stout: Physic. Rev. **59** (1941) 902.
(32) Hemmendinger, A.: Physic. Rev. **55** (1939) 604 (abs. 67); **58** (1940) 929.
(33) Henderson, M. C., M. St. Livingston & E. O. Lawrence: Physic. Rev. **45** (1934) 428.
(34) Henderson, M. C., M. St. Livingston & E. O. Lawrence: Physic. Rev. **46** (1934) 38.
(35) Henderson, M. C.: Physic. Rev. **48** (1935) 855.
(36) Henderson, W. J., L. N. Ridenour, M. G. White & M. C. Henderson: Physic. Rev. **51** (1937) 1107.
(37) Henderson, W. J. & L. N. Ridenour: Physic. Rev. **52** (1937) 40.
(38) Henderson, W. J. & R. L. Doran: Physic. Rev. **56** (1939) 123.
(39) Herb, R. G., D. W. Kerst & J. L. McKibben: Physic. Rev. **51** (1937) 691.
(40) Hevesy, G. v.: Nature, London **135** (1935) 96.
(41) Hevesy, G. v.: Kgl. Danske Acad. **13** (1935) Nr. 3.
(42) Hevesy, G. v. & H. Levy: Nature, London **135** (1935) 580.
(43) Hevesy, G. v. & H. Levy: Nature, London **136** (1935) 103.
(44) Hevesy, G. v. & H. Levy: Nature, London **137** (1936) 185.
(45) Hevesy, G. v. & H. Levy: Kgl. Danske Acad. **14** (1936) Nr. 5.
(46) Hevesy, G. v. & H. Levy: Kgl. Danske Acad. **15** (1938) Nr. 11.
(47) Heyden, M. & W. Wefelmeier: Naturwiss. **26** (1938) 612.
(48) Heyn, F. A.: Nature, London **138** (1936) 723.
(49) Heyn, F. A.: Physica **4** (1937) 160.
(50) Heyn, F. A.: Physica **4** (1937) 1224.
(51) Heyn, F. A.: Nature, London **139** (1937) 842.
(52) Heyn, F. A., A. H. W. Aten jr. & C. J. Bakker: Nature, London **143** (1939) 516.
(53) Hill, J. E. & G. E. Valley: Physic. Rev. **55** (1939) 678 (abs. 34).
(54) Hill, J. E.: Physic. Rev. **55** (1939) 1117 (abs. 38).
(55) Hill, J. E.: Physic. Rev. **57** (1940) 567 (abs. 57).
(56) Hill, J. E.: Physic. Rev. **57** (1940) 1076 (abs. 110).
(57) Hoag, J. B.: Physic. Rev. **57** (1940) 937.
(58) Hole, N., J. Holtsmark & R. Tangen: Naturwiss. **28** (1940) 399.
(59) Hole, N., J. Holtsmark & R. Tangen: Naturwiss. **28** (1940) 668.
(60) Holloway, M. G. & B. L. Moore: Physic. Rev. **56** (1939) 705.
(61) Holloway, M. G.: Physic. Rev. **57** (1940) 347 (abs. 17).
(62) Holloway, M. G. & H. A. Bethe: Physic. Rev. **57** (1940) 747.
(63) Holloway, M. G. & B. L. Moore: Physic. Rev. **57** (1940) 1086 (abs. 159).
(63a) Holloway, M. G. & B. L. Moore: Physic. Rev. **58** (1940) 847.
(64) Hosemann, R.: Z. Physik **99** (1936) 405.
(65) Houtermans, F. G.: Naturwiss. **28** (1940) 578.
(66) Huber, O., P. Huber & P. Scherrer: Helv. physic. Acta **13** (1940) 209, 212.
(67) Hudson, C. M., R. G. Herb & G. J. Plain: Physic. Rev. **57** (1940) 587.
(68) Hull, D. E., W. F. Libby & W. M. Latimer: J. Amer. chem. Soc. **57** (1935) 1649.
(68a) Humphreys, R. F. & E. Pollard: Physic. Rev. **59** (1941) 942 (abs. 145).
(69) Huntoon, R. D., A. Ellett, D. S. Bayley & T. A. van Allen: Physic. Rev. **58** (1940) 97.

(70) Hurst, D. G. & H. Walke: Physic. Rev. **51** (1937) 1033.
(71) Hurst, D. G., R. Latham & W. B. Lewis: Proc. roy. Soc. London (A) **147** (1940) 126.

(1) Imre, L.: Naturwiss. **28** (1940) 158.

(0) Jacobsen, I. C. & N. O. Lassen: Physic. Rev. **58** (1940) 867.
(1) Jaekel, R.: Z. Physik **96** (1935) 151.
(2) Jaekel, R.: Z. Physik **104** (1937) 762.
(3) Jaekel, R.: Z. Physik **107** (1937) 669; **110** (1938) 330.
(3a) Jensen, A. S.: Physic. Rev. **59** (1941) 936 (abs. 115).
(4) Jentschke, W., F. Prankl & F. Hernegger: Naturwiss. **28** (1940) 315. Mitt. d. Wiener Inst. Radiumforsch. Nr. 439, 27 June 1940.
(5) Johnson, C. H. & F. T. Hamblin: Nature, London **138** (1936) 504.

(1) Kalbfell, D. C.: Physic. Rev. **54** (1938) 543.
(2) Kalbfell, D. C. & R. A. Coolley: Physic. Rev. **58** (1940) 91.
(3) Kamen, M. D. & S. Ruben: Physic. Rev. **58** (1940) 194 (abs. 33).
(4) Kanne, W. R.: Physic. Rev. **52** (1937) 266.
(5) Kempton, A. E., B. C. Brown & R. Maasdorp: Proc. roy. Soc. London (A) **157** (1936) 372.
(6) Kennedy, J. W., G. T. Seaborg & E. Segré: Physic. Rev. **56** (1939) 1095.
(7) Kennedy, J. W. & G. T. Seaborg: Physic. Rev. **57** (1940) 843.
(8) Kikuchi, K., H. Aoki & K. Husimi: Nature, London **137** (1936) 186.
(9) Kikuchi, S., Y. Watase, J. Itoh, E. Takeda & S. Yamaguchi: Proc. physic.-math. Soc. Japan (3) **21** (1939) 260, 381.
(10) Kikuchi, S., Y. Watase, J. Itoh, E. Takeda & S. Yamaguchi: Proc. physic.-math. Soc. Japan (3) **21** (1939) 41, 52.
(11) Kimura, K.: Mem. Coll. Sci. Kyoto imp. Univ. **22** (1939) 237.
(12) King, L. D. P., W. J. Henderson & J. R. Risser: Physic. Rev. **55** (1939) 1118.
(13) King, L. D. P., W. J. Henderson: Physic. Rev. **56** (1939) 1169; **57** (1940) 71.
(13a) King, L. D. P. & D. R. Elliott: Physic. Rev. **58** (1940) 846.
(13b) King, L. D. P. & D. R. Elliott: Physic. Rev. **59** (1941) 108 (abs. 16).
(14) Kingdon, K. H., H. C. Pollock, E. T. Booth & J. R. Dunning: Physic. Rev. **57** (1940) 749.
(15) Kirchner, F. & H. Neuert: Physikal. Z. **35** (1932) 292.
(16) Kirchner, F : Physikal. Z. **34** (1933) 777.
(17) Kirchner, F. & H. Neuert: Physikal. Z. **36** (1935) 36.
(18) Kirchner, F., H. Neuert & O. Laaff: Physikal. Z. **38** (1937) 969.
(19) Klarmann, H.: Z. Physik **95** (1935) 221.
(20) Knol, K. S. & J. Veldkamp: Physica **3** (1936) 145.
(21) König, A.: Z. Physik **90** (1934) 197.
(22) Korsunsky, M. I., F. F. Lange & W. S. Spinell C. R. Acad. Sci. USSR. **26** (1940) 144.
(23) Kovarik, A. F. & N. J. Adams jr.: Physic. Rev. **54** (1938) 413.
(24) Kraus, J. D. & J. M. Cork: Physic. Rev. **51** (1937) 383.
(25) Kraus, J. D. & J. M. Cork: Physic. Rev. **52** (1937) 763.
(26) Krischnan. R. S. & D. H. T. Gant: Nature, London **144** (1939) 547.
(27) Krishnan, R. S. & T. E. Banks: Nature, London **145** (1940) 777.
(28) Krishnan, R. S. & T. E. Banks: Nature, London **145** (1940) 860.
(29) Kourtschatow, B., I. Kourtschatow, L. Myssowsky & L. Roussinow: C. R. Séances Acad. Sci. Paris **200** (1935) 1201.
(30) Kourtschatow, I., L. Nemenow & L. Selinow: C. R. Seances Acad. Sci. Paris **200** (1935) 2162.
(31) Kourtschatow, I. W., G. D. Latyschew, L. M. Nemenow & I. P. Selinow: Physikal. Z. USSR. **8** (1935) 589.
(32) Kuerti, G. & S. N. Van Voorhis: Physic. Rev. **56** (1939) 614.
(33) Kurie, F. N. D: Physic. Rev. **45** (1934) 904.
(34) Kurie, F. N. D.: Physic. Rev. **47** (1935) 97.
(35) Kurie, F. N. D., J. R. Richardson & H. C. Paxton: Physic. Rev. **49** (1936) 368.

(1) Laaff, O.: Ann. Physik **32** (1938) 743.
(1a) Langer, A. & W. E. Stephens: Physic. Rev. **58** (1940) 759.
(2) Langer, L. M., A. C. G. Mitchell & P. W. McDaniel: Physic. Rev. **56** (1939) 380.
(3) Langer, L. M., A. C. G. Mitchell & P. W. McDaniel: Physic. Rev. **56** (1939) 422.
(4) Langer, L. M., A. C. G. Mitchell & P. W. McDaniel: Physic. Rev. **56** (1939) 962.
(5) Langer, L. M., A. C. G. Mitchell & P. W. McDaniel: Physic. Rev. **57** (1940) 347 (abs. 15).
(6) Langsdorf, A. jr.: Physic. Rev. **56** (1939) 205.
(7) Langsdorf, A. jr. & E. Segré: Physic. Rev. **57** (1940) 105.
(8) Lark-Horovitz, K., J. R. Risser & R. N. Smith: Physic. Rev. **55** (1939) 878.
(9) Laslett, L. J.: Physic. Rev. **50** (1936) 388.
(10) Laslett, L. J.: Physic. Rev. **52** (1937) 529.
(11) Latimer, W. M., D. E. Hull & W. F. Libby: J. Amer. chem. Soc. **57** (1935) 781.
(12) Lauritsen, C. C. & H. R. Crane: Physic. Rev. **45** (1934) 63.
(13) Lauritsen, C. C. & W. A. Fowler: Physic. Rev. **58** (1940) 193 (abs. 32).
(13a) Lauritsen, T., C. C. Lauritsen & W. A. Fowler: Physic. Rev. **59** (1941) 241.
(13b) Law, H. B., M. L. Pool, J. D. Kurbatov & L. L. Quill: Physic. Rev. **59** (1941) 936 (abs. 116).
(14) Lawrance, A. M.: Proc. Cambridge phil. Soc. **35** (1939) 304.
(15) Lawrence, E. O., M. St. Livingston & G. N. Lewis: Physic. Rev. **44** (1933) 56.
(16) Lawrence, E. O. & M. St. Livingston: Physic. Rev. **45** (1934) 220.
(17) Lawrence, E. O.: Physic. Rev. **46** (1934) 746.
(18) Lawrence, E. O.: Physic. Rev. **47** (1935) 17.
(19) Lawrence, E. O., E. McMillan & M. C. Henderson: Physic. Rev. **47** (1936) 273.
(20) Lawson, J. L. & J. M. Cork: Physic. Rev. **52** (1937) 531.
(21) Lawson, J. L.: Physic. Rev. **56** (1939) 131.
(22) Lawson, J. L. & J. M. Cork: Physic. Rev. **57** (1940) 356 (abs. 57), 982.
(23) Lawson, J. L. & J. M. Cork: Physic. Rev. **58** (1940) 580.
(24) Lea, D. E.: Proc. roy. Soc. London (A) **150** (1935) 637.
(25) Lecoin, M.: J. Physiq. Radium (7) **9** (1938) 81.
(26) Lee, D. D. & W. F. Libby: Physic. Rev. **55** (1939) 252.
(27) Levi, H.: Nature, London **145** (1940) 571.
(28) Lewis, G. N., M. St. Livingston & E. O. Lawrence: Physic. Rev. **44** (1933) 55.

(29) Lewis, W. B., W. F. Burcham & W. Y. Chang: Nature, London **139** (1937) 24.
(30) Libby, W. F. & D. D. Lee: Physic. Rev. **55** (1939) 245.
(31) Libby, W. F.: Physic. Rev. **56** (1939) 21.
(32) Lieber, C.: Naturwiss. **27** (1939) 421.
(33) Livingood, J. J.: Physic. Rev. **50** (1936) 425.
(34) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **50** (1936) 435.
(35) Livingood, J. J., F. Fairbrother & G. T. Seaborg: Physic. Rev. **52** (1937) 135.
(36) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **52** (1937) 135.
(37) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **53** (1938) 765.
(38) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **53** (1938) 847.
(39) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **53** (1938) 1015.
(40) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **54** (1938) 51.
(41) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **54** (1938) 88.
(42) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **54** (1938) 239.
(43) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **54** (1938) 391.
(44) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **54** (1938) 775.
(45) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **55** (1939) 414.
(46) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **55** (1939) 457.
(47) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **55** (1939) 667.
(48) Livingood, J. J. & G. T. Seaborg: Physic. Rev. **55** (1939) 1268.
(49) Livingood, J. J. & G. T. Seaborg: To be published in Physic. Rev. See same authors: Rev. mod. Physics **12** (1940) 30 & G. T. Seaborg: Chem. Rev. **27** (1940) 199.
(49a) Livingood, J. J. & G. T. Seaborg: Unpublished research. See same authors: Rev. mod. Physics **12** (1940) 30.
(50) Livingston, M. St., M. C. Henderson & E. O. Lawrence: Physic. Rev. **44** (1933) 316.
(51) Livingston, M. St. & E. McMillan: Physic. Rev. **46** (1934) 437.
(52) Livingston, M. St & J. G. Hoffman: Physic. Rev. **50** (1936) 401.
(53) Livingston, M. St. & H. A. Bethe: Rev. mod. Physic. **9** (1937) 245.
(54) Livingston, M. St. & J. G. Hoffman: Physic. Rev. **53** (1938) 227.
(54a) Livingston, R. S. & B. T. Wright: Physic. Rev. **58** (1940) 656.
(55) Lyman, E. M.: Physic. Rev. **51** (1937) 1.
(56) Lyman, E. M.: Physic. Rev. **55** (1939) 234 (abs. 8), 1123 (abs. 65).

(1) Madsen, C. B.: Nature, London **138** (1936) 722.
(2) Magnan, C.: C. R. Séances Acad. Sci. Paris **205** (1937) 1147.
(3) Maier-Leibnitz, H. & W. Maurer: Z. Physik **107** (1937) 509.
(4) Maier-Leibnitz, H.: Naturwiss. **26** (1938) 614. Z. Physik **112** (1939) 569.
(5) Mann, W. B.: Physic. Rev. **52** (1937) 405.
(6) Mann, W. B.: Physic. Rev. **53** (1938) 212.
(7) Mann, W. B.: Physic. Rev. **54** (1938) 649.
(7a) Manning, H. P., C. M. Crenshaw & V. J. Young: Physic. Rev. **59** (1941) 941 (abs. 143).
(8) Marsh, J. K. & S. Sugden: Nature, London **136** (1935) 102.
(8a) Marshall, J. S.: Proc. roy. Soc. London (A) **173** (1939) 410.
(9) Mattauch, J.: Naturwiss. **25** (1937) 189.
(9a) Mattauch, J.: Physic. Rev. **57** (1940) 549.
(10) Maurer, W.: Z. Physik **107** (1937) 721.
(11) Maurer, W. & J. B. Fisk: Z. Physik **112** (1939) 436.
(11a) Maurer, W. & R. Ramm: Naturw. **29** (1941) 368.
(11b) Maurer, W. & R. Ramm: Private commun.
(12) May, A. N. & R. Vaidyanathan: Proc. roy. Soc. London (A) **155** (1936) 519.
(13) McCreary, R. L., G. Kuerti & S. N. Van Voorhis: Physic. Rev. **57** (1940) 351 (abs. 35).
(14) McLean, W. B., R. A. Becker, W. A. Fowler & C. C. Lauritsen: Physic. Rev. **55** (1939) 796.
(15) McLean, W. B., A. Ellett & J. A. Jacobs: Physic. Rev. **58** (1940) 500.
(16) McLennan, J. C., L. G. Grimmet & J. Read: Nature, London **135** (1935) 147.
(17) McLennan, J. C., L. G. Grimmet & J. Read: Nature, London **135** (1935) 505.
(18) McLennan, J. C. & W. H. Rann: Nature, London **136** (1935) 831.
(19) McMillan, E.: Physic. Rev. **46** (1934) 868.
(20) McMillan, E. & E. O. Lawrence: Physic. Rev. **47** (1935) 343.
(21) McMillan, E. & M. St. Livingston: Physic. Rev. **47** (1935) 452.
(22) McMillan, E.: Physic. Rev. **49** (1936) 875.
(23) McMillan, E., M. Kamen & S. Ruben: Physic. Rev. **52** (1937) 375.
(24) McMillan, E.: Physic. Rev. **55** (1939) 510.
(25) McMillan, E. & P. H. Abelson: Physic. Rev. **57** (1940) 1185.
(26) McMillan, E.: Physic. Rev. **58** (1940) 178.
(27) Meitner, L. & K. Philipp: Naturwiss. **20** (1932) 929.
(28) Meitner, L. & K. Philipp: Z. Physik **87** (1934) 484.
(29) Meitner, L., O. Hahn & F. Strassmann: Z. Physik **106** (1937) 249.
(30) Meitner, L., F. Strassmann & O. Hahn: Z. Physik **109** (1938) 538.
(31) Meitner, L.: Nature, London **145** (1940) 422; Ark. Mat., Astron. och Fys. (A) **27** (1941) Nr. 17.
(32) Meye, A.: Z. Physik **105** (1937) 232.
(33) Meyer, St., V. F. Hess & F. Paneth: S. B. Akad. Wiss. Wien, Math.-naturwiss. Kl. IIa **123** (1914) 1459.
(34) Miller, H., W. E. Duncanson & A. N. May: Proc. Cambridge phil. Soc. **30** (1934) 549.
(34a) Miller, L.: Physic. Rev. **58** (1940) 935.
(35) Minakawa, O.: Physic. Rev. **57** (1940) 1189.
(36) Mitchell, D. P., F. Rasetti, G. A. Fink & G. B. Pegram: Physic. Rev. **50** (1936) 189.
(37) Mitchell, A. C. G.: Physic. Rev. **51** (1937) 995.
(38) Mitchell, A. C. G. & L. M. Langer: Physic. Rev. **52** (1937) 137.
(39) Mitchell, A. C. G.: Physic. Rev. **53** (1938) 269.
(40) Mitchell, A. C. G. & L. M. Langer: Physic. Rev. **53** (1938) 505.
(41) Mitchell, A. C. G., L. M. Langer & P. W. McDaniel: Physic. Rev. **57** (1940) 347 (abs. 16).
(42) Mitchell, A. C. G., L. M. Langer & P. W. McDaniel: Physic. Rev. **57** (1940) 1107.
(43) Moore, B. L.: Physic. Rev. **57** (1940) 355 (abs. 56).
(43a) Mulder, D., G. W. Hocksema & G. J. Sizoo: Physica **7** (1940) 849.
(44) Murrell, E. B. M. & C. L. Smith: Proc. roy. Soc. London (A) **173** (1939) 410.

(1) Nahmias, M. E.: C. R. Séances Acad. Sci. Paris **202** (1936) 71.
(2) Nahmias, M. E. & R. J. Walen: C. R. Séances Acad. Sci. Paris **203** (1936) 71. J. Physiq. Radium **8** (1937) 153.
(3) Naidu, R.: Nature, London **137** (1936) 578.
(4) Naidu, R. & R. E. Siday: Proc. physic. Soc. London **48** (1936) 332.
(5) Neary, G. J.: Proc. roy. Soc. London (A) **175** (1940) 71.
(5a) Nemilow, J. A.: J. exp. theoret. Physik (russ.) **9** (1939) 1029.
(6) Neuninger, E. & E. Rona: Wien. Akad. Anz. Nr. 27 of 12 December 1935. Nature, London **137** (1936) 711.
(7) Neuninger, E. & E. Rona: Wien. Akad. Anz. Nr. 17 of 2 July 1936.
(8) Neuert, H.: Physikal. Z. **36** (1935) 629.
(9) Neuert, H.: Ann. Physik **36** (1939) 437.
(10) Newson, H. W.: Physic. Rev. **48** (1935) 482.
(11) Newson, H. W.: Physic. Rev. **48** (1935) 790.
(12) Newson, H. W.: Physic. Rev. **51** (1937) 620.
(13) Newson, H. W.: Physic. Rev. **51** (1937) 624.
(14) Newson, H. W. & L. B. Borst: Physic. Rev. **57** (1940) 1083 (abs. 145).
(14a) Newson, H. W. & L. B. Borst: Physic. Rev. **59** (1941) 941 (abs. 142).
(15) Nier, A. O.: Physic. Rev. **35** (1939) 153.
(16) Nier, A. O., E. T. Booth, J. R. Dunning & A. V. Grosse: Physic. Rev. **57** (1940) 546.
(17) Nier, A. O., E. T. Booth, J. R. Dunning & A. V. Grosse: Physic. Rev. **57** (1940) 748.
(18) Nishina, Y., T. Yasaki, K. Kimura & M. Ikawa: Nature, London **142** (1938) 874.
(19) Nishina, Y., T. Yasaki, H. Ezoe, K. Kimura & M. Ikawa: Physic. Rev. **57** (1940) 1182.
(19a) Nishina, Y., T. Yasaki, K. Kimura & M. Ikawa: Physic. Rev. **58** (1940) 660. — Y. Nishina, T. Yasaki, H. Ezoe, K. Kimura & M. Ikawa: Nature, London **146** (1940) 24.
(19b) Nishina, Y., T. Yasaki, K. Kimura & M. Ikawa: Physic. Rev. **59** (1941) 323, 677.
(20) Norling, F.: Z. Physik **111** (1938) 158.
(21) Norling, F.: Naturwiss. **27** (1939) 432.
(22) Northrup, D. L., C. M. van Atta, R. J. van de Graaff & L. C. van Atta: Physic. Rev. **58** (1940) 199 (abs. 3).

(1) Oeser, E. A. & J. L. Tuck: Nature, London **139** (1937) 1110.
(2) Oldenberg, O.: Physic. Rev. **53** (1938) 35.
(3) Oliphant, M. L. E. & Lord Rutherford: Proc. roy. Soc. London (A) **141** (1933) 259.
(4) Oliphant, M. L. E., B. B. Kinsey & Lord Rutherford: Proc. roy. Soc. London (A) **141** (1933) 722.
(5) Oliphant, M. L. E., P. Harteck & Lord Rutherford: Proc. roy. Soc. London (A) **144** (1934) 692. Nature, London **133** (1934) 413.
(6) Oliphant, M. L., E. S. Shire & B. M. Crowther: Nature, London **133** (1934) 377.
(7) Oliphant, M. L., E. S. Shire & B. M. Crowther: Proc. roy. Soc. London (A) **146** (1934) 922.
(8) Oliphant, M. L.: Int. Conf. Phys. London 1934.
(9) Oliphant, M. L. E., A. R. Kempton & Lord Rutherford: Proc. roy. Soc. London (A) **149** (1935) 406.
(10) Oliphant, M. L. E., A. E. Kempton & Lord Rutherford: Proc. roy. Soc. London (A) **150** (1935) 241.
(10a) Ollano, Z.: Nuovo Cim. **18** (1941) 11.
(11) O'Neal, R. D. & M. Goldhaber: Physic. Rev. **57** (1940) 1086 (abs. 142).
(12) O'Neal, R. D. & M. Goldhaber: Physic. Rev. **58** (1940) 574.
(12a) O'Neal, R. D.: Physic. Rev. **59** (1941) 109 (abs. 19).
(13) Oppenheimer, F. & E. P. Tomlinson: Physic. Rev. **56** (1939) 858 (abs. 49).
(14) Ortner, G.: Z. Physik **89** (1934) 711.
(15) Ortner, G. & G. Protiwinsky: Anz. Akad. Wien **1939**, S. 116, Nr. 18/19. S. B. Akad. Wiss. Wien, Math.-naturwiss. Kl. **148** (1939) 349.

(1) Park, R. D. & J. C. Mouzon: Physic. Rev. **58** (1940) 43.
(2) Paton, R. F.: Physic. Rev. **46** (1934) 229.
(3) Paton, R. F.: Physic. Rev. **47** (1935) 197.
(3a) Pecher, Ch.: Physic. Rev. **58** (1940) 843.
(4) Perey, Mlle. M.: C. R. Séances Acad. Sci. Paris **208** (1939) 97. J. Physiq. Radium **10** (1939) 435.
(5) Perey, Mlle. M. & M. Lecoin: Nature, London **144** (1939) 326.
(6) Perey, Mlle. M. & M. Lecoin: J. Physiq. Radium **10** (1939) 439.
(7) Perlow, G. J.: Physic. Rev. **58** (1940) 218.
(8) Perrier, Cl., M. Santangelo & E. Segre: Physic. Rev. **53** (1938) 104.
(9) Plain, G. T., R. G. Herb, C. M. Hudson & R. E. Warren: Physic. Rev. **57** (1940) 187.
(9a) Plesset, E. H.: Physic. Rev. **59** (1941) 936 (abs. 118).
(10) Polessitsky, A.: Physikal Z. USSR. **12** (1937) 339.
(11) Polessitsky, A. & M. Orbeli: C. R. Acad. Sci. USSR. **28** (1940) 215, 217.
(12) Pollard, E.: Proc. Leeds phil. Lit. Soc. **2** (1932) 324.
(13) Pollard, E. & C. J. Brasefield: Physic. Rev. **50** (1936) 890.
(14) Pollard, E. & C. J. Brasefield: Physic. Rev. **51** (1937) 8.
(15) Pollard, E., H. L. Schultz & G. Brubaker: Physic. Rev. **51** (1937) 140.
(16) Pollard, E., H. L. Schultz & G. Brubaker: Physic. Rev. **53** (1938) 351.
(17) Pollard, E.: Physic. Rev. **54** (1938) 411.
(18) Pollard, E.: Physic. Rev. **56** (1939) 961.
(19) Pollard, E.: Physic. Rev. **56** (1939) 1168.
(20) Pollard, E.: Physic. Rev. **57** (1940) 241.
(21) Pollard, E. & W. W. Watson: Physic. Rev. **57** (1940) 567 (abs. 59).
(22) Pollard, E.: Physic. Rev. **57** (1940) 1086 (abs. 158).
(23) Pollard, E. & W. W. Watson: Physic. Rev. **58** (1940) 12.
(23a) Pollard, E. & F. Humphreys: Physic. Rev. **59** (1941) 466 (abs. 4).
(24) Pontecorvo, B.: Physic. Rev. **54** (1938) 542. C. R. Séances Acad. Sci. Paris **207** (1938) 423.
(25) Pontecorvo, B. & A. Lazar: C. R. Séances Acad. Sci. Paris **208** (1939) 99.
(26) Pool, M. L., J. M. Cork & R. L. Thornton: Physic. Rev. **51** (1937) 890.
(27) Pool, M. L. & J. M. Cork: Physic. Rev. **51** (1937) 1010 (abs. 66).
(28) Pool, M. L., J. M. Cork & R. L. Thornton: Physic. Rev. **52** (1937) 239.
(29) Pool, M. L., J. M. Cork & R. L. Thornton: Physic. Rev. **52** (1937) 380.
(30) Pool, M. L.: Physic. Rev. **53** (1938) 116.
(31) Pool, M. L. & L. L. Quill: Physic. Rev. **33** (1938) 437.
(32) Pose, H.: Physikal. Z. **30** (1929) 780. Z. Physik **64** (1930) 1; **95** (1935) 84.
(33) Pose, H.: Physikal. Z. **37** (1936) 154.
(34) Preiswerk, P. & H. v. Halban jr.: C. R. Séances Acad. Sci. Paris **201** (1935) 722.

(1) Rajam, J. B., P. C. Capron & M. de Hemptinne: Nature, London **144** (1939) 202.
(2) Rajam, J. B., P. C. Capron & M. de Hemptinne: Ann. Soc. sci. Bruxelles, Ser. I **59** (1939) 403.
(3) Rasetti, F.: Z. Physik **97** (1935) 64.
(3a) Rayton, W. M. & T. R. Wilkins: Physic. Rev. **51** (1937) 818.
(4) Reddemann, H. & F. Strassmann: Naturwiss. **25** (1938) 187.
(5) Reddemann, H. & F. Strassmann: Naturwiss. **25** (1938) 458.
(6) Reddemann, H.: Naturwiss. **28** (1940) 110.
(7) Reddemann, H.: Z. Physik **116** (1940) 137.
(7a) Richards, H. T.: Physic. Rev. **59** (1941) 796.
(8) Richardson, J. R. & L. Emo: Physic. Rev. **53** (1938) 234.
(9) Richardson, J. R.: Physic. Rev. **55** (1939) 609.
(10) Richardson, J. R. & F. N. D. Kurie: Physic. Rev. **50** (1936) 999.
(11) Richardson, J. R.: Physic. Rev. **53** (1938) 124.
(12) Richardson, J. R.: Physic. Rev. **53** (1938) 610.
(13) Ridenour, L. N., W. J. Henderson, M. C. Henderson & M. G. White: Physic. Rev. **51** (1937) 1013.
(14) Ridenour, L. N. & W. J. Henderson: Physic. Rev. **51** (1937) 1102.
(15) Ridenour, L. N. & W. J. Henderson: Physic. Rev. **52** (1937) 139.
(16) Ridenour, L. N. & W. J. Henderson: Physic. Rev. **52** (1937) 889.
(17) Ridenour, L. N., L. A. Delsasso, M. G. White & R. Sherr: Physic. Rev. **53** (1938) 770.
(17a) Ringo, R.: Physic. Rev. **58** (1940) 942; **59** (1941) 107 (abs. 10).
(18) Risser, J. R.: Physic. Rev. **52** (1937) 768.
(19) Risser, J. A., K. Lark-Horovitz & R. N. Smith: Physic. Rev. **57** (1940) 355 (abs. 55).
(20) Roberts, R. B., N. P. Heydenburg & C. L. Locher: Physic. Rev. **53** (1938) 1016.
(21) Rogers, F. T. jr. & M. M. Rogers: Physic. Rev. **55** (1939) 263.
(22) Rogers, M. M., W. E. Bennett, T. W. Bonner & E. Hudspeth: Physic. Rev. **58** (1940) 186.
(23) Rona, E. & H. Scheichenberger: Wien. Akad. Anz. Nr. 8 of 17 March 1938.
(24) Rose, M. E.: Physic. Rev. **53** (1938) 844.
(25) Rotblat, J.: Nature, London **136** (1935) 515.
(26) Rotblat, J.: Nature, London **138** (1936) 202.
(27) Rotblat, J. Nature, London **139** (1937) 1110.
(28) Rotblat, J.: Nature, London **144** (1939) 248.
(29) Roussinow, L. I. & A. A. Yusephovich: C. R. Acad. Sci. USSR. **24** (1939) 129.
(30) Ruben, S. & M. D. Kamen: Physic. Rev. **57** (1940) 549.
(31) Ruben, S. & M. D. Kamen: Priv. comm. to J. J. Livingood & G. T. Seaborg: Rev. mod. Physics **12** (1940) 30.
(31a) Ruben, S.: Physic. Rev. **59** (1941) 216 (abs. 7).
(31b) Ruben, S. & M. D. Kamen: Physic. Rev. **59** (1941) 349.
(32) Rumbaugh, L. H. & L. R. Hafstad: Physic. Rev. **50** (1936) 681.
(33) Rumbaugh, L. H., R. B. Roberts & L. R. Hafstad: Physic. Rev. **51** (1937) 143.
(34) Rumbaugh, L. H., R. B. Roberts & L. R. Hafstad: Physic. Rev. **54** (1938) 657.
(35) Rusinov, L.: Physikal. Z. USSR. **10** (1936) 219.
(36) Rutherford, Sir E. & J. Chadwick: Phil. Mag. J. Sci. **42** (1921) 809.
(37) Rutherford, E. & J. Chadwick: Nature, London **113** (1924) 457.

(1) Sagane, R.: Physic. Rev. **50** (1936) 1141.
(2) Sagane: R.: Physic. Rev. **53** (1938) 212.
(3) Sagane, R., S. Kojima & M. Ykawa: Physic. Rev. **54** (1938) 149.
(4) Sagane, R., S. Kojima, G. Miyamoto & M. Ykawa: Physic. Rev. **54** (1938) 542.
(5) Sagane, R., S. Kojima, G. Miyamoto & M. Ykawa: Physic. Rev. **54** (1938) 970.
(6) Sagane, R.: Physic. Rev. **55** (1939) 31.
(7) Sagane, R., S. Kojima, G. Miyamoto & M. Ikawa: Proc. physic.-math. Soc. Japan (3) **21** (1939) 660.
(8) Sagane, R., S. Kojima & G. Miyamoto: Proc. physic.-math. Soc. Japan (3) **21** (1939) 728.
(9) Sagane, R., S. Kojima, G. Miyamoto & M. Ikawa: Physic. Rev. **57** (1940) 750.
(10) Sagane, R., S. Kojima, G. Miyamoto & M. Ikawa: Physic. Rev. **57** (1940) 1179.
(11) Sagane, R., S. Kojima, G. Miyamoto & M. Ikawa: Proc. physic.-math. Soc. Japan (3) **22** (1940) 174.
(11a) Sagane, R., G. Miyamoto & M. Ikawa: Physic. Rev. **59** (1941) 904.
(12) Saha, N. K.: Z. Physik **110** (1938) 473.
(13) Saha, N. K.: Naturwiss. **27** (1939) 786.
(14) Sampson, M. B., L. N. Ridenour & W. Bleakney: Physic. Rev. **50** (1936) 382.
(15) Sargent, B. W.: Proc. roy. Soc. London (A) **139** (1933) 659.
(16) Sargent, B. W.: Canad. J. Res. (A) **17** (1939) 82. Physic. Rev. **54** (1938) 232.
(17) Sargent, B. W.: Canad. J. Res. (A) **17** (1939) 103.
(18) Savel, P.: C. R. Séances Acad. Sci. Paris **198** (1934) 368.
(19) Savel, P.: C. R. Séances Acad. Sci. Paris **198** (1934) 1404.
(20) Savel, P.: Ann. Physique **4** (1935) 88.
(21) Schaeffer, W. & P. Harteck: Z. Physik **113** (1939) 287.
(21a) Scharff-Goldhaber, G.: Physic. Rev. **59** (1941) 937 (abs. 119).
(22) Scheichenberger, H.: Wien. Akad. Anz. Nr. 17 of 20 October 1938.
(22a) Schintlmeister, J.: Sitzgsber. Akad. Wiss. Wien, Abt. IIa, **146** (1937) 371.
(23) Schultz, H. L.: Physic. Rev. **53** (1938) 622.
(23a) Schultz, H. L., W. L. Davidson & L. H. Ott: Physic. Rev. **58** (1940) 1043.
(23b) Schultz, H. L. & W. W. Watson: Physic. Rev. **58** (1940) 1047.
(24) Seaborg, G. T. & J. W. Kennedy: Physic. Rev. **55** (1939) 410.
(25) Seaborg, G. T., J. J. Livingood & J. W. Kennedy: Physic. Rev. **55** (1939) 794.
(26) Seaborg, G. T. & E. Segré: Physic. Rev. **55** (1939) 808.
(27) Seaborg, G. T., J. J. Livingood & J. W. Kennedy: Physic. Rev. **57** (1940) 363.
(27a) Seaborg, G. T., J. J. Livingood & F. Friedlander: Physic. Rev. **59** (1941) 320.
(27b) Seaborg, G. T., J. W. Gofman & J. W. Kennedy: Physic. Rev. **59** (1941) 321.
(27c) Seaborg, G. T. & G. Friedlander: Physic. Rev. **59** (1941) 400.
(28) Seelmann-Eggebert, W.: Naturwiss. **28** (1940) 451.
(29) Seelmann-Eggebert, W.: Diss. Berlin 1940.
(30) Segrè, E., R. S. Halford & G. T. Seaborg: Physic. Rev. **55** (1939) 321.
(31) Segrè, E.: Physic. Rev. **55** (1939) 1104.

(31a) Segrè, E. & G. T. Seaborg: Physic. Rev. **59** (1941) 212.
(31b) Segrè, E. & C. S. Wu: Private communcation to G. T. Seaborg: Chem. Rev. **27** (1940) 199.
(32) Shrader, E. F. & E. Pollard: Physic. Rev. **58** (1940) 199 (abs. 4).
(33) Segré, E. & C. S. Wu: Physic. Rev. **57** (1940) 552.
(34) Sherr, R.: Physic. Rev. **57** (1940) 937.
(34a) Sherr, R. & K. T. Bainbridge: Physic. Rev. **59** (1941) 937 (abs. 122).
(34b) Shrader, E. F. & E. Pollard: Physic. Rev. **59** (1941) 277.
(35) Simma, K. & F. Yamasaki: Sci. Pap. Inst. physic. chem. Res. Japan **35** (1938) 16.
(36) Simma, K. & F. Yamasaki: Physic. Rev. **55** (1939) 320.
(37) Sizoo, G. J. & C. Eijkman: Physica **6** (1939) 332.
(38) Skaggs, L. S. & E. R. Graves: Physic. Rev. **57** (1940) 1087 (abs. 163).
(39) Smith, C. L. & E. B. M. Murrell: Proc. Cambridge phil. Soc. **35** (1939) 298.
(39a) Smith, E. & E. Pollard: Physic. Rev. **59** (1941) 942 (abs. 146).
(40) Smith, N. M. jr.: Physic. Rev. **56** (1939) 548.
(40a) Smith G. P.: Physic. Rev. **59** (1941) 937 (abs. 121).
(41) Snell, A. H.: Physic. Rev. **49** (1936) 555.
(42) Snell, A. H.: Physic. Rev. **51** (1937) 143.
(43) Snell, A. H.: Physic. Rev. **51** (1937) 1011 (abs. 69).
(44) Snell, A. H.: Physic. Rev. **52** (1937) 1007.
(45) Soltan, A. & L. Wertenstein: Nature, London **141** (1938) 76.
(46) Starke, K.: Naturwiss. **28** (1940) 631.
(47) Staub, H. & W. E. Stephens: Physic. Rev. **55** (1939) 845.
(48) Stegmann, H.: Z. Physik **95** (1935) 72.
(49) Steudel, E.: Z. Physik **77** (1932) 139.
(50) Stephens, W. E.: Physic. Rev. **53** (1938) 223.
(51) Stetter, G.: Z. Physik **100** (1936) 652.
(52) Stetter, G. & W. Jentschke: Z. Physik **110** (1938) 214.
(53) Stewart, D. W., J. L. Lawson & J. M. Cork: Physic. Rev. **52** (1937) 901.
(54) Stewart, D. W.: Physic. Rev. **56** (1939) 629.
(55) Strain, C. V.: Physic. Rev. **54** (1938) 1021.
(56) Strassmann, F. & E. Walling: Ber. Deutsch. chem. Ges. **71** (1938) 1.
(56a) Streib, J. F., W. A. Fowler & C. C. Lauritsen: Physic. Rev. **59** (1941) 253.
(57) Sugden, S.: Nature, London **135** (1935) 469.
(58) Szalay, A.: Z. Physik **112** (1939) 29.
(59) Szalay, A. & J. Zimonyi: Z. Physik **115** (1940) 639.
(60) Szilard, L. & T. A. Chalmers: Nature, London **134** (1934) 494.
(61) Szilard, L. & T. A. Chalmers: Nature, London **135** (1935) 98.

(1) Tape, G. F. & J. M. Cork: Physic. Rev. **53** (1938) 676 (abs. 9).
(2) Tape, G. F.: Physic. Rev. **55** (1939) 1135 (abs. 125).
(3) Tape, G. F.: Physic. Rev. **56** (1939) 965.
(4) Taylor, H. J.: Proc. physic. Soc. London **47** (1935) 873.
(5) Taylor, H. J. & V. D. Dabholkar: Proc. physic. Soc. London **48** (1936) 285.
(6) Thornton, R. L.: Physic. Rev. **49** (1936) 207.
(7) Thornton, R. L. & J. M. Cork: Physic. Rev. **51** (1937) 383 (abs. 51).
(8) Thornton, R. L.: Physic. Rev. **51** (1937) 893.
(9) Thornton, R. L.: Physic. Rev. **53** (1938) 326.
(9a) Townsend, A. A.: Proc. roy. Soc. London A **177** (1941) 357.
(10) Traubenberg, H. Rausch v., A. Eckhardt & R. Gebauer: Z. Physik **80** (1933) 557.
(11) Tuck, J. L.: J. chem. Soc. **1939**, 1293.
(11a) Turner, L. A.: Physic. Rev. **58** (1940) 679.
(12) Tuve, M. A. & L. R. Hafstad: Physic. Rev. **45** (1934) 651.
(13) Tyler, A. W.: Physic. Rev. **55** (1939), 1136 (abs. 127); **56** (1939) 125.

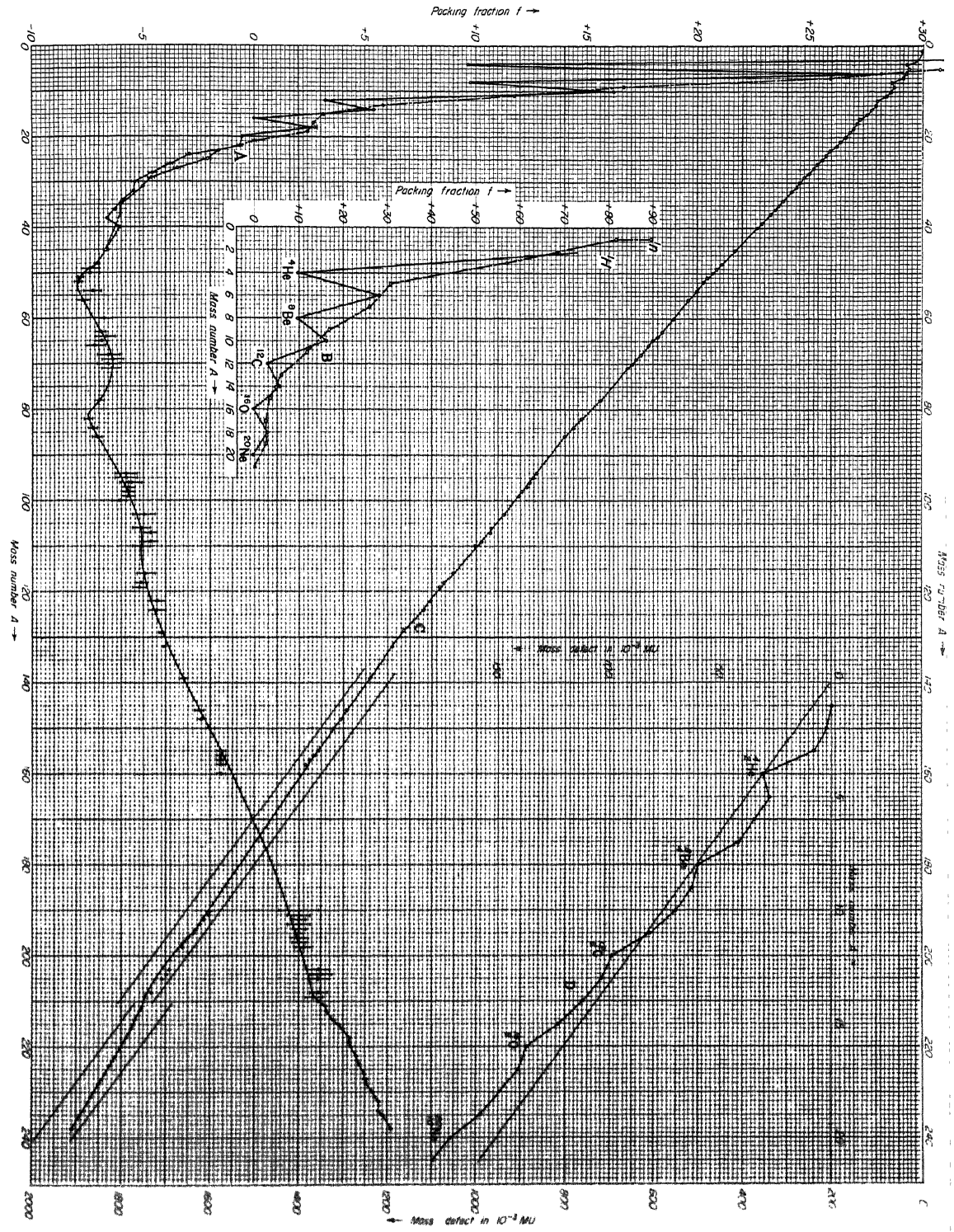
(1) Valley, G. E. & R. L. McCreary: Physic. Rev. **55** (1939) 666.
(2) Valley, G. E.: Physic. Rev. **56** (1939) 838.
(3) Valley, G. E. & R. L. McCreary: Physic. Rev. **56** (1939) 863.
(3a) Valley, G. E.: Physic. Rev. **59** (1941) 686 (abs. 22).
(3b) Van Allen, J. A. & N. M. Smith, jr.: Physic. Rev. **59** (1941) 108 (abs. 15), 501.
(3c) Van Allen, J. A. & N. M. Smith, jr.: Physic. Rev. **59** (1941) 618.
(4) Van Voorhis, S. N.: Physic. Rev. **49** (1936) 889.
(5) Van Voorhis, S. N.: Physic. Rev. **50** (1936) 895.
(6) Van Voorhis, S. N.: Priv. comm. to J. J. Livingood & G. T. Seaborg: Rev. mod. Physics **12** (1940) 30.
(7) Veldkamp, J. & K. S. Knol: Physica **4** (1937) 166.
(8) Veldkamp, J. & H. de Vries: Physica **4** (1937) 1229.
(9) Victorin, O.: Proc. Cambridge phil. Soc. **34** (1938) 612. Chem. Listy Vědu Průmysl **33** (1939) 190.
(10) Voge, H. H.: J. Amer. chem. Soc. **61** (1939) 1032.
(11) Vries, H. de & J. Veldkamp: Physica **5** (1938) 249.
(12) Vries, H. de & G. Diemer: Physica **6** (1939) 599.

(1) Walen, R. J. & M. E. Nahmias: C. R. Séances Acad. Sci. Paris **203** (1937) 1149.
(1a) Waldman, B. & G. B. Collins: Physic. Rev. **57** (1940) 338.
(2) Walke, H.: Physic. Rev. **51** (1937) 439.
(3) Walke, H.: Physic. Rev. **52** (1937) 400.
(4) Walke, H.: Physic. Rev. **52** (1937) 669.
(5) Walke, H.: Physic. Rev. **52** (1937) 663.
(6) Walke, H.: Physic. Rev. **52** (1937) 777.
(7) Walke, H., E. J. Williams & G. R. Ivans: Proc. roy. Soc. London (A) **171** (1939) 360.
(8) Walke, H.: Physic. Rev. **57** (1940) 163.
(9) Walke, H., E. C. Thompson & J. Holt: Physic. Rev. **57** (1940) 171.
(10) Walke, H., F. C. Thompson & J. Holt: Physic. Rev. **57** (1940) 177.
(11) Walke, H.: Priv. comm. to J. J. Livingood & G. T. Seaborg: Rev. mod. Physic. **12** (1940) 30.
(12) Ward, A. G.: Proc. Cambridge phil. Soc. **35** (1939) 523.
(12a) Watase, Y. & J. Itoh: Proc. physic.-math. Soc. Japan (3) **21** (1939) 389.
(12b) Watase, Y. & J. Itoh: Proc. physic.-math. Soc. Japan (3) **21** (1939) 623.
(12c) Watase, Y., J. Itoh & E. Takeda: Proc. physic.-math. Soc. Japan (3) **22** (1940) 90.
(12d) Watson, W. W. & E. Pollard: Physic. Rev. **57** (1940) 1082 (abs. 137).
(13) Weil, G. L. & W. H. Barkas: Physic. Rev. **56** (1939) 485.
(14) Weisskopf, V. F. & D. H. Eving: Physic. Rev. **57** (1940) 472.

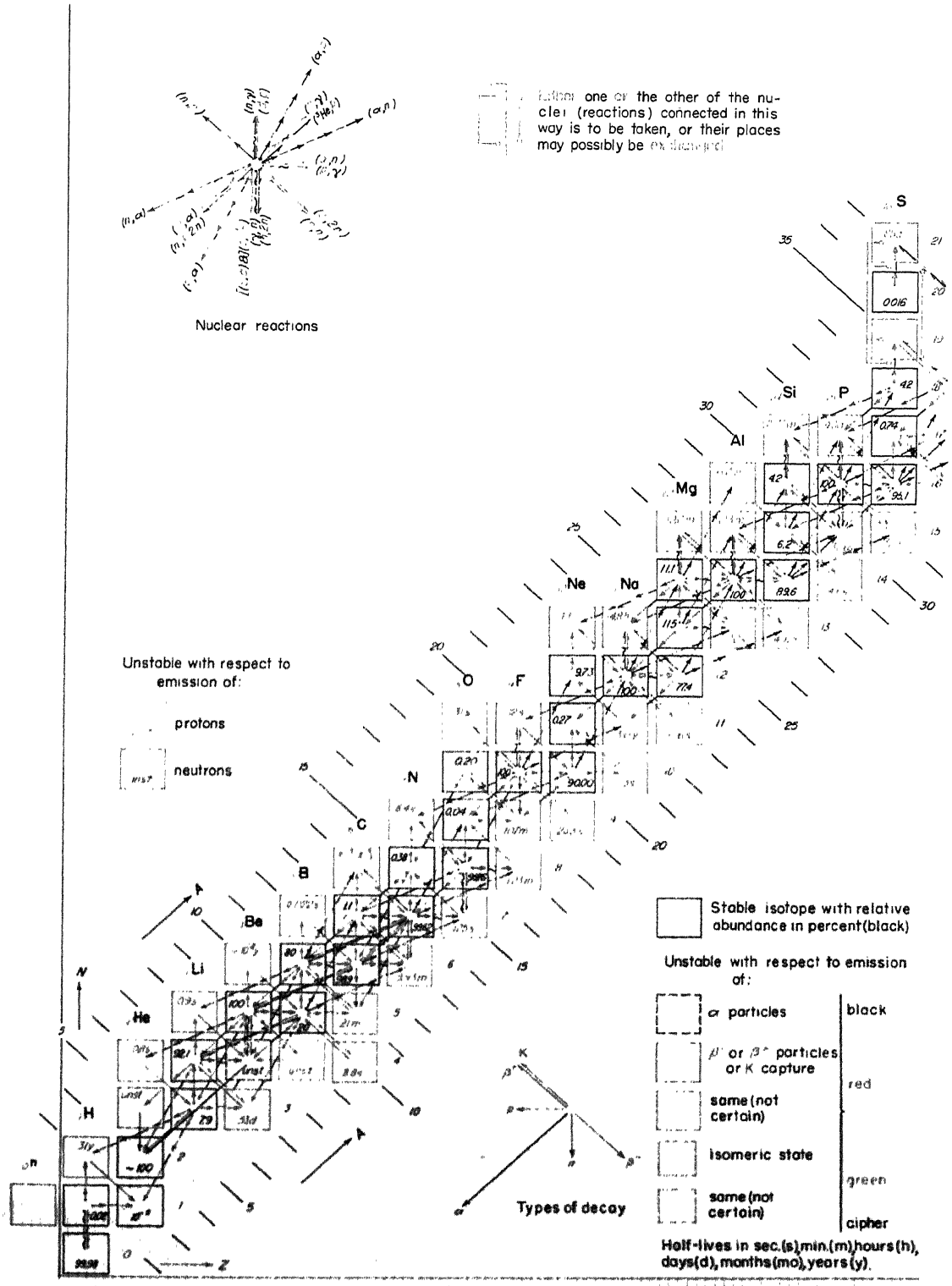
(14a) Welles, S B.: Physic. Rev. **59** (1941) 679, 920 (abs. 31).
(15) Wertenstein: Nature, London **133** (1934) 564.
(16) White, M. G., L. A. Delsasso, J. G. Fox & E. C. Creutz: Physic. Rev. **56** (1939) 512.
(16a) White, M. G., E. C. Creutz, L. A. Delsasso & R. R. Wilson: Physic. Rev. **59** (1941) 63.
(17) Widdowson, E. E. & F. C. Champion: Proc. physic. Soc. London **50** (1938) 185.
(17a) Wiens, J & L. W. Alvarez: Physic. Rev. **58** (1940) 1005.
(18) Wilhelmy, E.: Z. Physik **107** (1937) 769.
(18a) Wilkins, R. T. & D. P. Crawford: Physic. Rev. **54** (1938) 316.
(19) Williams, J. H., W. G. Shepherd & R. O. Haxby: Physic. Rev. **51** (1937) 888; **52** (1937) 390.
(20) Wilson, R. S.: Proc. roy. Soc. A **177** (1941) 382.
(20a) Winand, L.: J. Physique et Radium **8** (1937) 429.
(21) Wu, C. S.: Physic. Rev. **58** (1940) 926.
(22) Wu, C. S.: Physic. Rev. **59** (1941) 481.
(0) Yamaguchi, S.: Proc. phys.-math. Soc. Japan (3) **23** (1941) 264.
(1) Yamasaki, F. & K. Simma: Sci. Pap. Inst. physic. chem. Res. Japan **37** (1940) 10.
(2) Yasaki, T. & S. Watanabe: Nature, London **141** (1938) 787.
(3) Yasaki, T.: Sci. Pap. Inst. physic. chem. Res. Japan **37** (1940) 457.
(4) Yates, E. L.: Proc. roy. Soc. London **168** (1938) 148.
(5) Yost, D. M., L. N. Ridenour & K. Shinohara: J. chem. Physics **3** (1935) 133.
(6) Young, V. J., G. J. Plain, W. B. McLean & A. Ellett: Physic. Rev. **57** (1940) 1083 (abs. 142).
(7) Young, V. J., A. Ellett & G. T. Plain: Physic. Rev. **58** (1940) 498.

(1) Zingg, E.: Helv. physic. Acta **13** (1940) 219.
(2) Zyw, M.: Nature, London **134** (1934) 64.

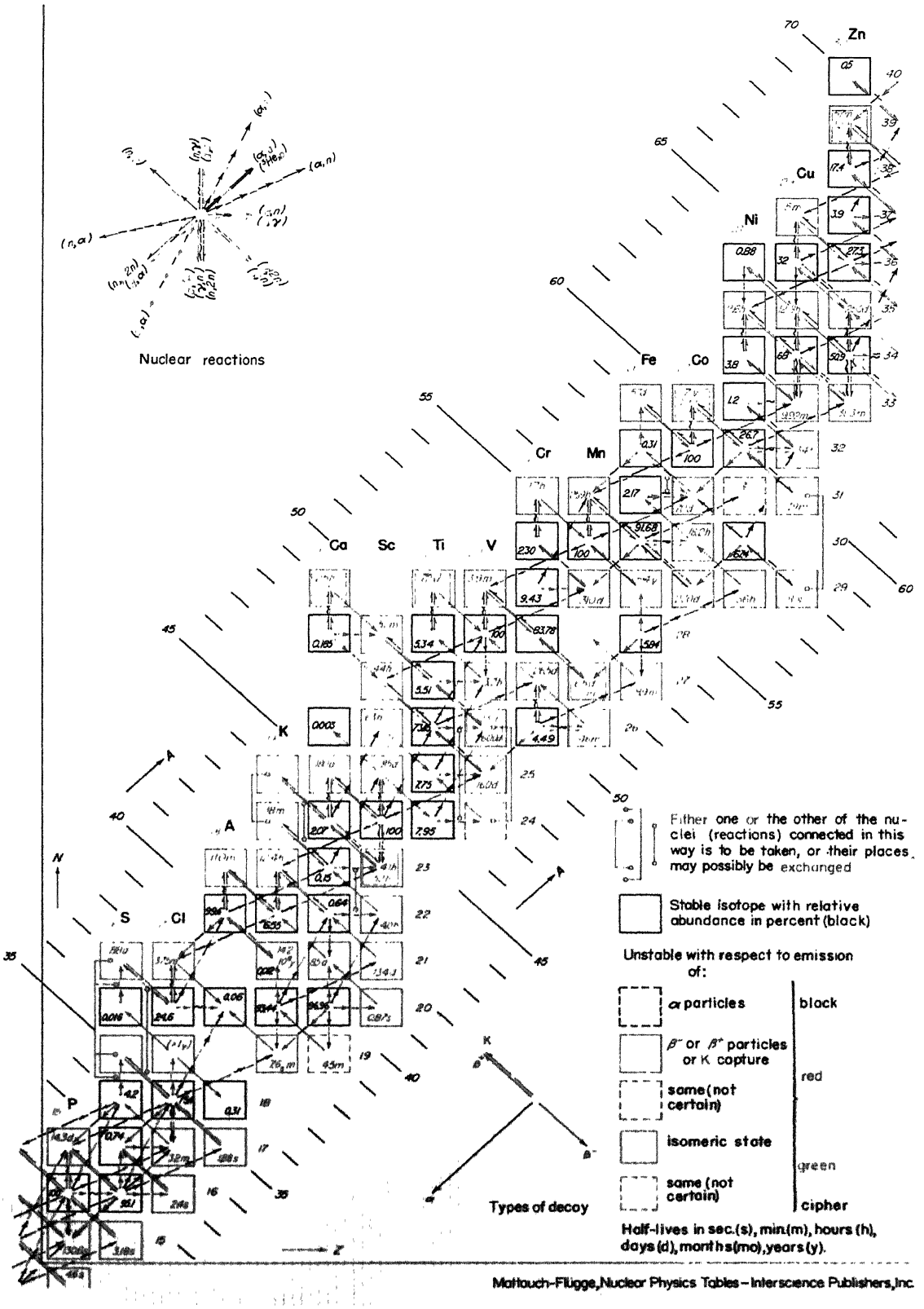
Nuclear Physics PLATES



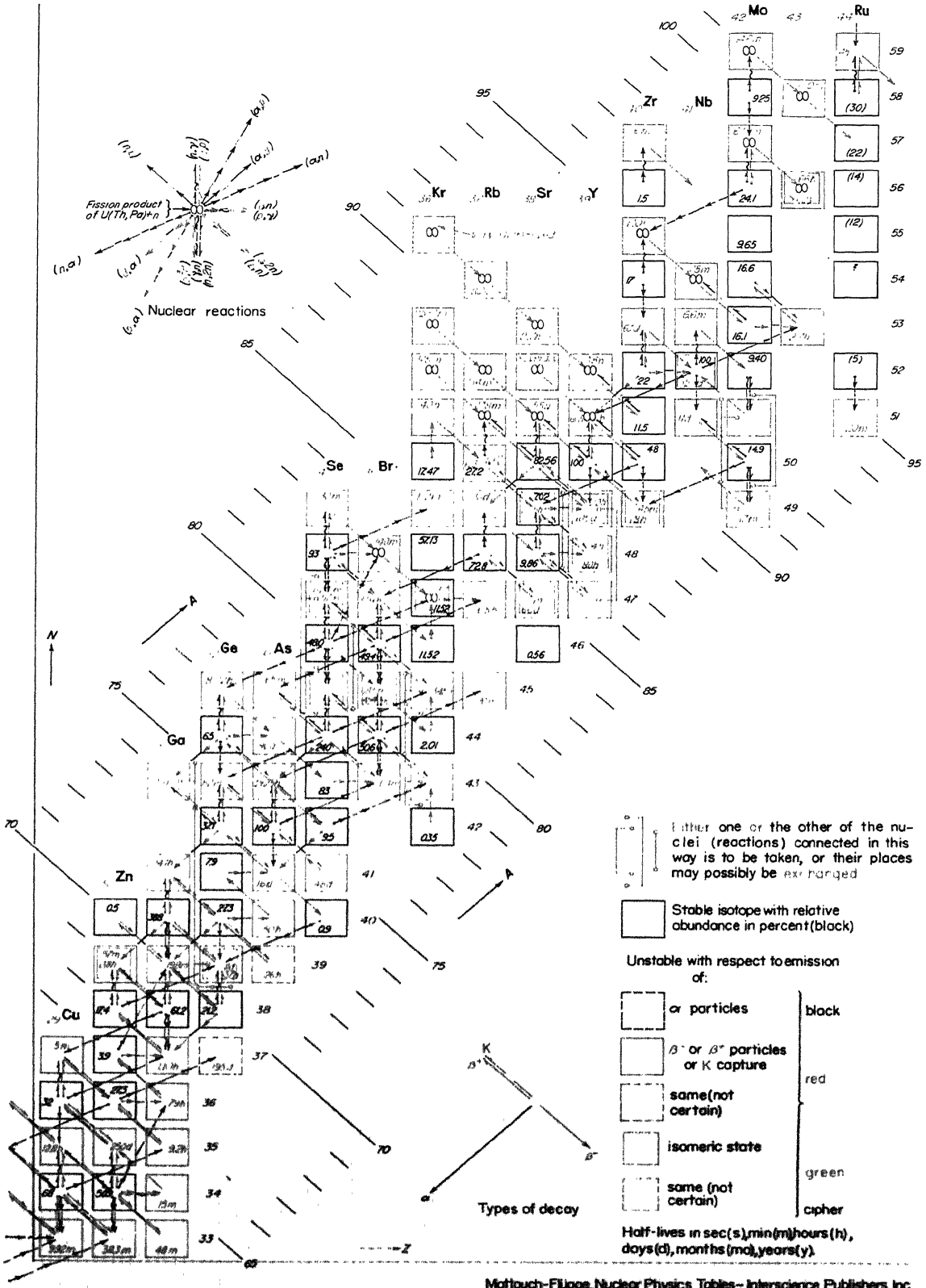
Mattauch-Flugge, Nuclear Physics Tables - Interscience Publishers, Inc



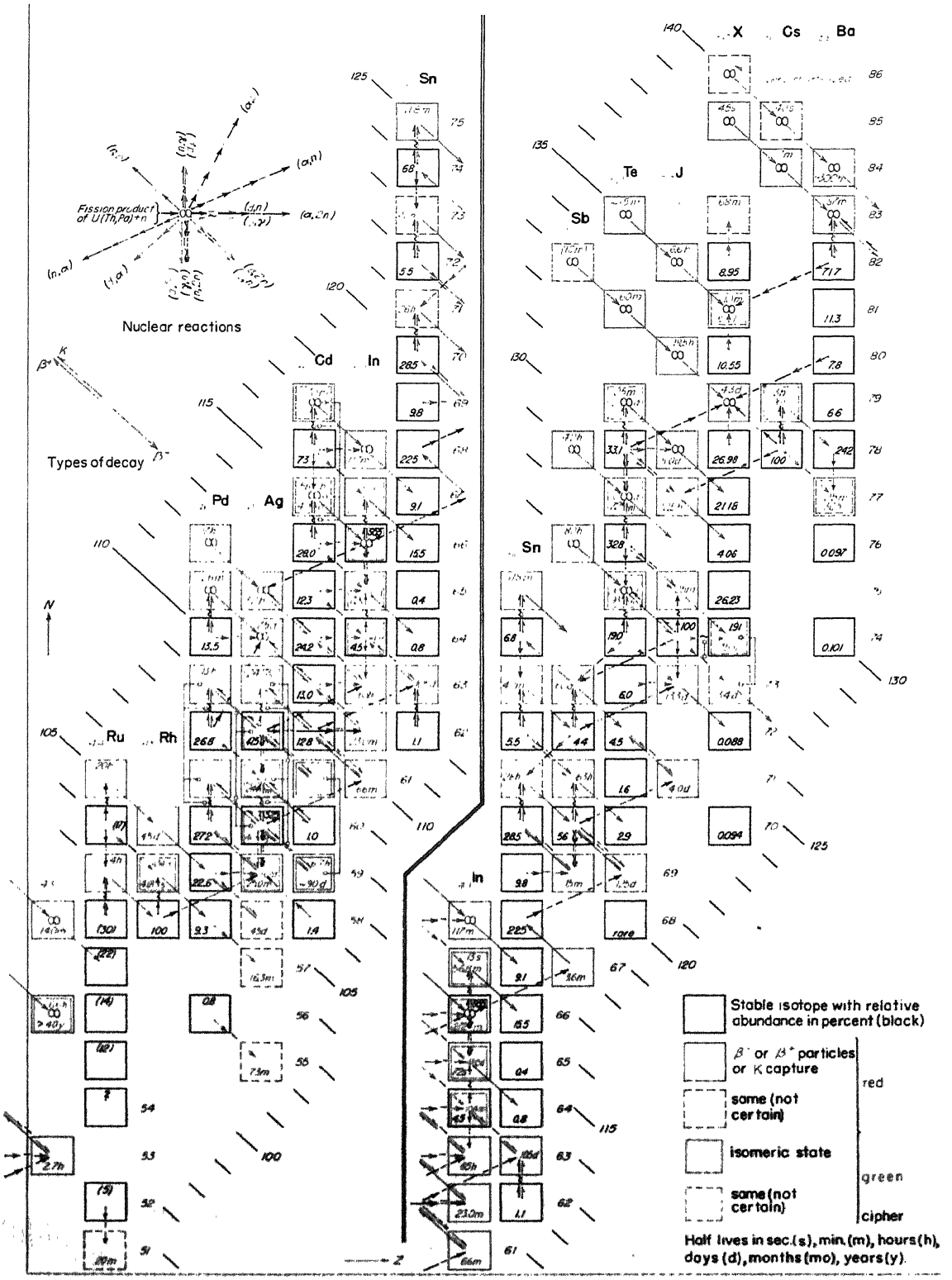
Mattauch-Flügge, Nuclear Physics Tables – Interscience Publishers, Inc.



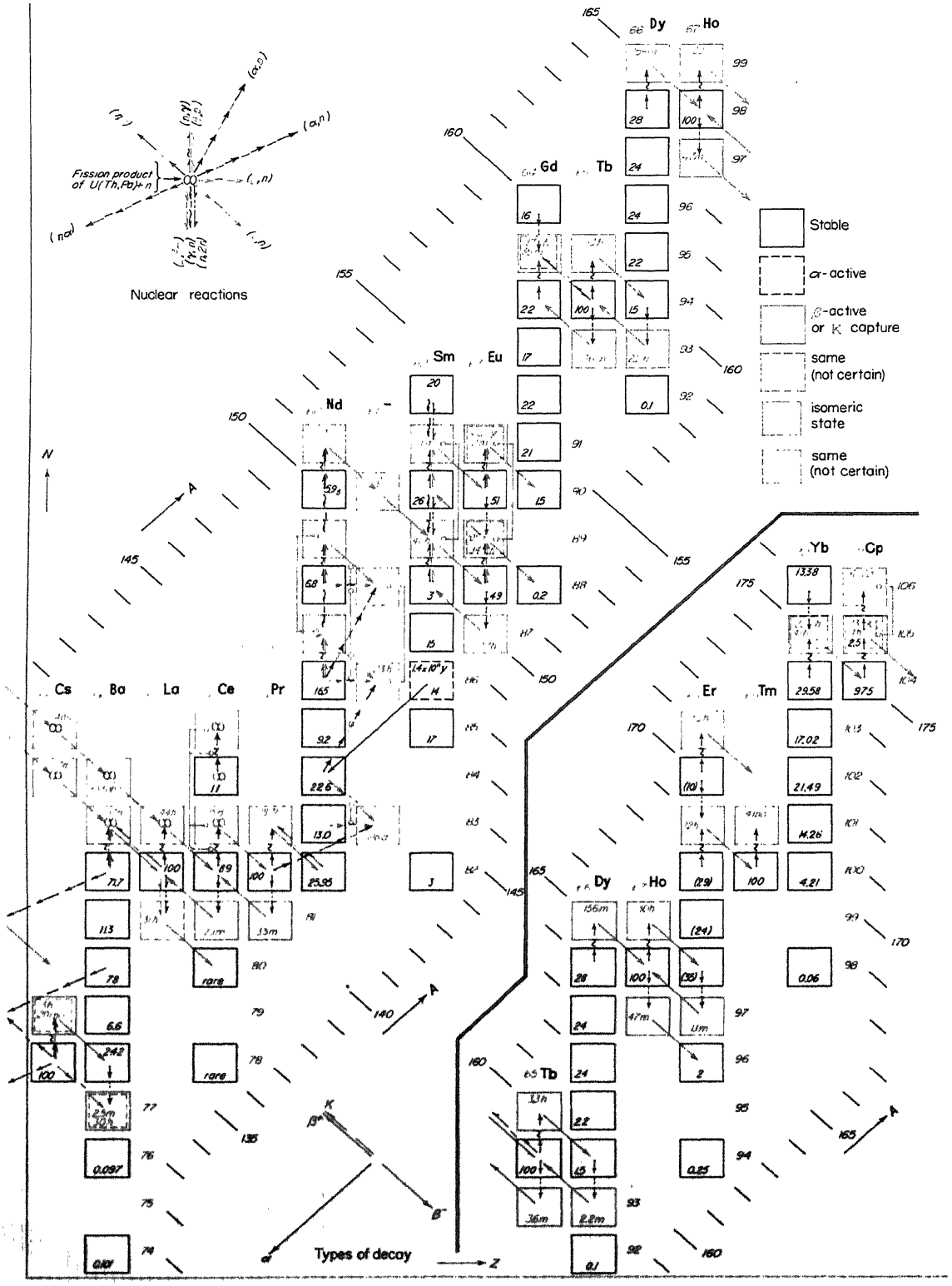
Mattauch-Flügge, Nuclear Physics Tables – Interscience Publishers, Inc.



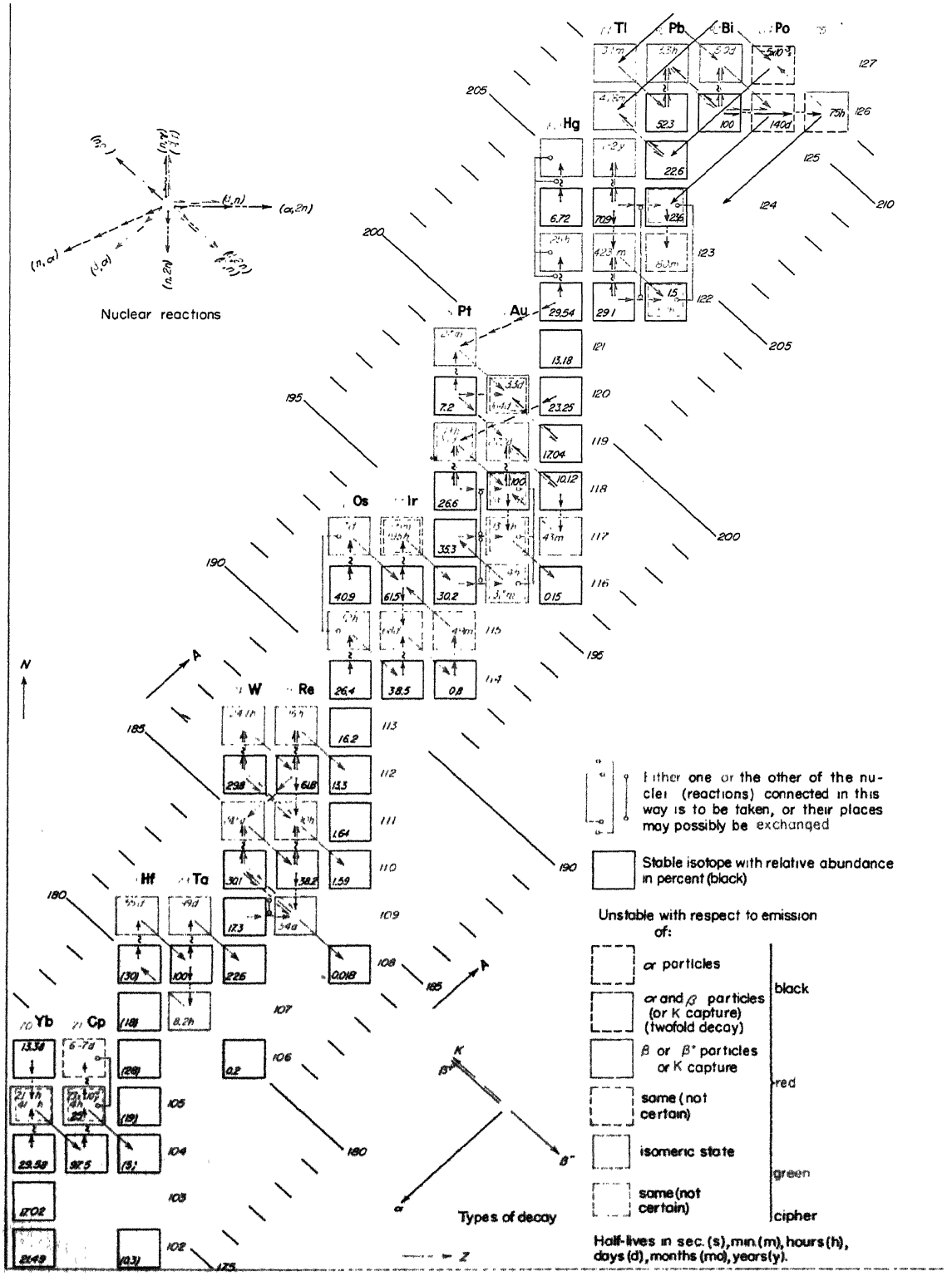
Mattauch-Flügge, Nuclear Physics Tables – Interscience Publishers, Inc.



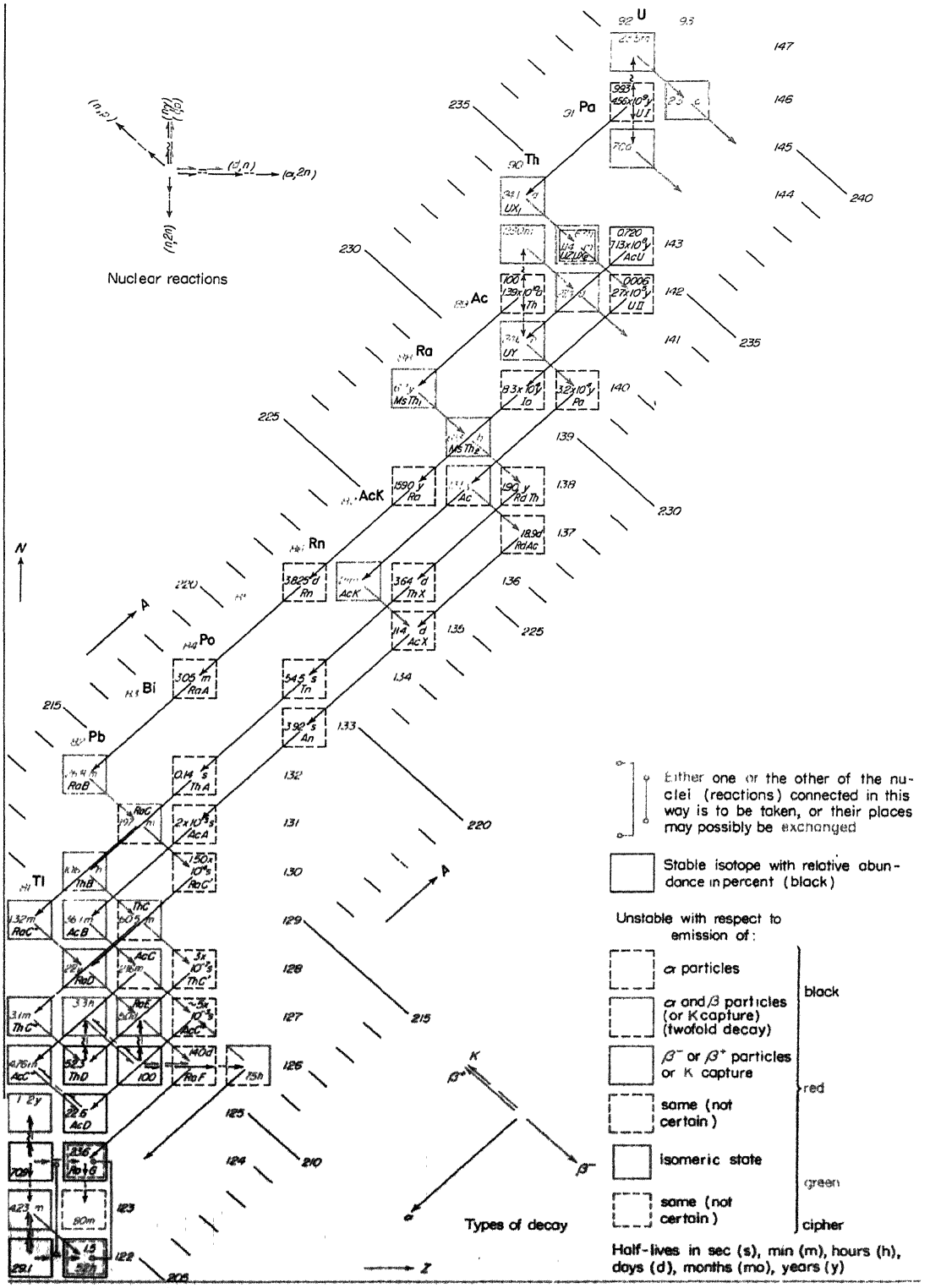
Mattauch-Flügge, Nuclear Physics Tables - Interscience Publishers, Inc



Mattauch-Flügge, Nuclear Physics Tables – Interscience Publishers, Inc.



Mattauch-Flügge, Nuclear Physics Tables - Interscience Publishers, Inc



Mattauch-Flügge, Nuclear Physics Tables - Interscience Publishers, Inc.

2769